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GLOBAL EDITION

The Nature and Properties of Soils

FIFTEENTH EDITION

Ray R. Weil • Nyle C. Brady

Pearson

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GLOBAL EDITION

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To all the students and colleagues in soil science who have shared their inspirations, camaraderie, and deep love of the Earth.

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Nyle C. Brady 1920–2015

On 24 November 2015 soil science lost one of its giants. Nyle C. Brady passed away at the age of 95. Dr. Brady was a global leader in soil science, in agriculture, and in humanity. He was born in 1920 in the tiny rural town of Manassa, Colorado, USA. He earned a BS degree in chemistry from Brigham Young University in 1941 and went on to complete his PhD in soil science at North Carolina State University in 1947. Dr. Brady then served as a member of the faculty at Cornell University in New York, USA for 26 years, rising from assistant professor to professor and chair of the agronomy department and finally to Assistant Dean of the College of Agriculture. During this period, he was elected President of both the American Society of Agronomy and of the Soil Science Society of America.

Soon after arriving at Cornell University he was recruited by Professor Harry O. Buckman to assist in co-authoring the then already classic soil science textbook, *The Nature and Properties of Soils*. The first edition of this textbook to bear Nyle Brady's name as co-author was published in 1952. Under Nyle's hand this book rose to prominence throughout the world and several generations of soil scientists got their introduction to the field through its pages. He was the sole author of editions published between 1974 in 1990. He continued to work on revised editions of this book with co-author Ray Weil until 2004. In recognition of his influence on the 15th edition, Dr. Brady continues to be listed as co-author of this textbook and his name is widely known and respected throughout the world in this capacity.

Dr. Brady was of that generation of American soil scientists that contributed so much to the original green revolution. He conducted research into the chemistry of phosphorus and the management of fertilizers and he was an early researcher on minimum tillage. Known for his active interest in international development and for his administrative skills, he was recruited in 1973 to be the third Director General of the International Rice Research Institute (IRRI) in the Philippines. Dr. Brady pioneered new cooperative relationships between IRRI and the national agricultural research institutions in many Asian countries, including a breakthrough visit to China at a time when that country was still quite closed to the outside world. He oversaw the transition to a second-generation of green revolution soil management and plant breeding designed to overcome some of the shortcomings of the first generation.

After leaving IRRI, he served as Senior Assistant Administrator for Science and Technology at the U.S. Agency for International Development from 1981 to 1989. He was a fierce champion of international scientific cooperation to promote sustainable resource use and agricultural development.

During the 1990s Dr. Brady, then in his 70s, served as senior international development consultant for the United Nations Development Programme (UNDP) and for the World Bank, in which capacity he continued to promote scientific collaboration in advances in environmental stewardship and agricultural development.

Dr. Brady was always open-minded and ready to accept new truths supported by scientific evidence, as can be seen by the evolution of the discussion of such topics as pesticide use, fertilizer management, manure utilization, tillage, soil organic matter, and soil acidity management in *The Nature and Properties of Soils* under his guidance. Nyle Brady had a larger-than-life personality, a deep sense of empathy,

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and an incredible understanding of how to work with people to get positive results. He was the kind of person that friends, associates, and even strangers would go to for advice when they found themselves in a perplexing position as a scientist, administrator, or even in their personal life. Dr. Brady is survived by his beloved wife, Martha, two daughters, a son (a second son preceded him in death), 22 grandchildren, and 90 great grandchildren. He will be very much missed for a long time to come by his family and by all who knew him or were touched by his work.

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Preface

By opening this 15th edition of *The Nature and Properties of Soils*, you are tapping into a narrative that has been at the forefront of soil science for more than a century. The first version, published in 1909, was largely a guide to good soil management for farmers in the glaciated regions of New York State in the northeastern United States. Since then, it has evolved to provide a globally relevant framework for an integrated understanding of the diversity of soils, the soil system, and its role in the ecology of planet Earth. This latest edition is the first to feature *full color illustrations* throughout.

If you are a student reading this, you have chosen a truly auspicious time to take up the study of soil science. This new edition was completed as the United Nations and countries around the world celebrated the International Year of Soils (2015). Soils are now widely recognized as the underpinning of terrestrial ecosystems and the source of a wide range of essential ecosystem services. An understanding of the soil system is therefore critical for the success and environmental harmony of almost any human endeavor on the land. This importance of soils and soil science is increasingly recognized by business and political leaders, by the scientific community, and by those who work with the land.

Scientists and managers well versed in soil science are in short supply and becoming increasingly sought after. Much of what you learn from these pages will be of enormous practical value in equipping you to meet the many natural-resource challenges of the 21st century. You will soon find that the soil system provides many opportunities to see practical applications for principles from such sciences as biology, chemistry, physics, and geology.

This newest edition of *The Nature and Properties of Soils* strives to explain the fundamental principles of Soil Science in a manner that you will find relevant to your interests. Throughout, the text emphasizes the soil as a natural resource and soils as ecosystems. It highlights the many interactions between soils and other components of forest, range, agricultural, wetland, and constructed ecosystems. This book will serve you well, whether you expect this to be your only formal exposure to soil science or you are embarking on a comprehensive soil science education. It will provide both an exciting, accessible introduction to the world of soils and a reliable, comprehensive reference that you will want to keep for your expanding professional bookshelf.

If you are an instructor or a soil scientist, you will benefit from changes in this latest edition. Most noticeable is the use of full-color throughout which improves the new and refined figures and illustrations to help make the study of soils more efficient, engaging, and intellectually satisfying. Every chapter has been thoroughly updated with the latest advances, concepts, and applications. Hundreds of new key references have been added. This edition includes in-depth discussions on such topics of cutting edge soil science as the pedosphere concept, new insights into humus and soil carbon accumulation, subaqueous soils, soil effects on human health, principles and practice of organic farming, urban and human engineered soils, cycling and plant use of silicon, inner- and outer-sphere complexes, radioactive soil contamination, new understandings of the nitrogen cycle, cation saturation and ratios, acid sulfate soils, water-saving irrigation techniques, hydraulic redistribution, cover crop effects on soil health, soil food-web ecology, disease suppressive soils, soil microbial genomics, indicators of soil quality, soil ecosystem services, biochar, soil interactions with global climate change, digital soil maps, and many others.

In response to their popularity in recent editions, I have also added many new boxes that present either fascinating examples and applications or technical details and calculations. These boxes both *highlight* material of special interest and allow the

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logical thread of the regular text to flow smoothly without digression or interruption. Examples of applications boxes or case study vignettes include:

- "Dirt for Dinner"
- "Subaqueous Soils—Underwater Pedogenesis"
- "Practical Applications of Unsaturated Water Flow in Contrasting Layers"
- "Char: Is Black the New Gold?"
- "Where have All the Humics Gone?"
- "Tragedy in the Big Easy—A Levee Doomed to Fail"
- "Costly And Embarrassing Soil pH Mystery"
- "Gardeners' Friend not Always so Friendly
- "Soil Microbiology in the Molecular Age"
- "The Law of Return Made Easy: Using Human Urine"

Boxes also are provided to explain detailed calculations and practical numerical problems. Examples include:

- "Estimating CEC and Clay Mineralogy"
- "Calculating Lime Needs Based on pH Buffering"
- "Leaching Requirement for Saline Soils"
- "Calculation of Percent Pore Space in Soils"
- "Calculating Soil CEC From Lab Data"
- "Toward a Global Soil Information System"
- "Calculation of Nitrogen Mineralization"
- "Calculating a Soil-Quality Index for Plant Productivity"

As the global economy expands exponentially societies face new challenges with managing their natural resources. Soil as a fundamental natural resource is critical to sustained economic growth and the prosperity of people in all parts of the world. To achieve balanced growth with a sustainable economy while improving environmental quality, it will be necessary to have a deep understanding of soils, including their properties, functions, ecological roles, and management. I have written this textbook in a way designed to engage inquisitive minds and challenge them to understand soils and actively do their part as environmental and agricultural scientists, in the interest of ensuring a prosperous and healthy future for humanity on planet Earth.

This understanding must include the role of healthy soils in agricultural applications and the pressing need for increasing food production. However, it must also include knowledge of the many other ecosystem services provided by soils. In this textbook I have tried to take a broad view of soils in the environment and in relation to human society. In so doing, the book focuses on six major ecological roles of soil. Soils provide for the growth of plants, which, in turn, provide wildlife habitat, food for people and animals, bio-energy, clothing, pharmaceuticals, and building materials. In addition to plant production, soils also dramatically influence the Earth's atmosphere and therefore the direction of future climate change. Soils serve a recycling function that, if taken advantage of, can help societies to conserve and reuse valuable and finite resources. Soils harbor a large proportion of the Earth's biodiversity—a resource which modern technology has allowed us to harness for any number of purposes. Water, like soil, will be a critical resource for the future generations. Soils functions largely determine both the amount of water that is supplied for various uses and also the quality and purification of that water. Finally, knowledge of soil physical properties and behavior, as well as an understanding of how different soils relate to each other in the landscape, will be critical for successful and sustainable engineering projects aimed at effective and safe land development.

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For all these reasons it will be essential for the next generation of scientists, business people, teachers, and other professionals to learn enough about soils to appreciate their importance and to take them into full consideration for development projects and all activities on the land. It is my sincere hope that this book, early editions of which have served so many generations of soil students and scientists, will allow new generations of future soil scientists to benefit from the global ecological view of soils that this textbook expounds.

Dr. Nyle Brady, although long in retirement and recently deceased, remains as co-author in recognition of the fact that his vision, wisdom, and inspiration continue to permeate the entire book. Although the responsibility for writing the 15th edition was solely mine, I certainly could not have made all of the many improvements without innumerable suggestions, ideas, and corrections contributed by soil scientists, instructors, and students from around the world. The 15th edition, like preceding editions, has greatly benefited from the high level of professional devotion and camaraderie that characterizes the global soil science community.

Special thanks go to Dr. Rachel Gilker for her invaluable editorial and research assistance. I also thank the following colleagues (listed alphabetically by institution) for their especially valuable suggestions, contributions, reviews, and inspiration: Pichu Rengasamy (The University of Adelaide); Michéli Erika (Univ. Agricultural Science, Hungary); Duane Wolf (University of Arkansas); Tom Pigford (University of California, Berkeley); Thomas Ruehr (Cal Poly State University); J. Kenneth Torrence (Carleton University); Pedro Sanchez and Cheryl Palm (Columbia University); Harold van Es and Johannes Lehmann (Cornell University); Eric Brevik (Dickinson State University); Dan Richter (Duke University); Owen Plank (University of Georgia); Robert Darmody, Laura Flint Gentry, Colin Thorn, and Michelle Wander (University of Illinois); Roland Buresh (International Rice Research Institute); Lee Burras (Iowa State University); Aurore Kaisermann (Laboratoire Bioemco); Daniel Hillel (University of Massachusetts, Emeritus); Lyle Nelson (Mississippi State University, Emeritus); Jimmie Richardson (North Dakota State University); Rafiq Islam and Rattan Lal (The Ohio State University); David Munn (Ohio State ATI); Darrell Schultze (Purdue University); Joel Gruver (Western Illinois University); Ivan Fernandez (University of Maine); David Lobb (University of Manitoba); Mark Carroll, Glade Dlott, Delvin Fanning, Nicole Fiorellino, Robert Hill, Bruce James, Natalie Lounsbury, Brian Needelman, Martin Rabenhorst, Patricia Steinhilber, and Stephane Yarwood (University of Maryland); Martha Mamo (University of Nebraska); Jose Amador (University of Rhode Island); Russell Briggs (State University of New York); Allen Franzluebbers, Jeff Herrick, Scott Lesch, and Jim Rhoades (USDA/Agricultural Research Service); Bob Ahrens, Bob Engel, Maxine Levine, Paul Reich, Randy Riddle, Kenneth Scheffe, and Sharon Waltman (USDA/Natural Resources Conservation Service); Markus Kleber (Oregon State University); Henry Lin (The Pennsylvania State University); Joseph Heckman (Rutgers, The State University of New Jersey); Fred Magdoff and Wendy Sue Harper (University of Vermont); W. Lee Daniels, John Galbraith (Virginia Tech); Peter Abrahams (University of Wales); Luther Carter (Washington, DC); Clay Robinson (West Texas A & M University); Tor-G. Vagen (World Agroforestry Center); Larry Munn (University of Wyoming); and Tom Siccama (Yale University).

Last, but not least, I deeply appreciate the good humor, forbearance, and patience of my wife, Trish, and those students and colleagues who may have felt some degree of neglect as I focused so much of my energy, time, and attention on this labor of love.

RRW
College Park, Maryland, USA
February 2016

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Earth, our unique soil- and water-covered planet. (NASA)

1 The Soils Around Us

For in the end we will conserve only what we love.
We will love only what we understand.
And we will understand only what we are taught.
—*Baba Dioum*, African Conservationist

The Earth, our only home in the vastness of the universe, is unique for living systems sustained by its air, water, and soil resources. Among the millions of life forms on our planet, one species, the human species, has become so dominant that the quality of those resources now depends on that species learning to exercise a whole new level of stewardship.

Human activities are changing the very nature of the Earth's ecology. Some 50% of the land surface has been appropriated for human use. Depletion of stratospheric ozone is threatening to overload us with ultraviolet radiation. Emissions of carbon dioxide, nitrogen oxides, and methane gases are warming the planet and destabilizing the global climate. Tropical rain forests, and their incredible array of plants and animals, are disappearing at an unprecedented rate. Groundwater supplies are being contaminated and depleted. In parts of the world, the capacity of soils to produce food is being degraded, even as the number of people needing food is increasing. Bringing the global environment back into balance may well be the defining challenge for the current generation of students studying soils.

Soils[1] are crucial to life on Earth. To a great degree, the quality of the soil present determines the nature of plant ecosystems and the capacity of land to support animal life and society. Soils also play a central role in many of today's environmental challenges. From water pollution and climate change to biodiversity loss and human food supply, the world's ecosystems are impacted in far-reaching ways by processes carried out in the soil. As human societies become increasingly urbanized, fewer people have intimate contact with the soil, and individuals tend to lose sight of the many ways in which they depend upon soils for their prosperity and survival. Indeed, the degree to which we are dependent on soils is likely to increase, not decrease, in the future.

Soils will continue to supply us with nearly all of our food, yet how many of us remember, as we eat a slice of pizza, that the pizza's crust began in a field of wheat and its cheese began with grass, clover, and corn rooted in the soils of a dairy farm? Most of the fiber we use for lumber, paper, and clothing has its roots in the soils of forests and farmland. Although we sometimes use plastics and fiber synthesized from fossil petroleum as substitutes, in the long term we will continue to depend on terrestrial ecosystems for these needs.

In addition, biomass grown on soils is likely to become an increasingly important feedstock for fuels and manufacturing as the world's finite supplies of petroleum are depleted during the course of this century. The early marketplace signs of this trend can be

[1]Throughout this text, bold type indicates key terms whose definitions can be found in the glossary.

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Figure 1.1 *Environmental and economic imperatives suggest that we will become more dependent on soil to produce renewable materials that can substitute for increasingly scarce and environmentally damaging nonrenewables. Biodiesel fuel* (left) *produced from soybean and other oil crops is far less polluting and has less impact on global warming than petroleum-based diesel fuel. Other oil crops can substitute for petroleum to produce nontoxic inks* (bottom), *plastics, and other products. Cornstarch can be made into biodegradable plastics for such products as plastic bags and foam-packing "peanuts"* (upper right). (Photos courtesy of Ray R. Weil)

seen in the form of ethanol and biodegradable plastics synthesized from corn or biodiesel fuels and printers' inks made from soybean oil (Figure 1.1).

One of the stark realities of the 21st century is that the population of humans that demands all of these products will increase by several billion (population is expected to stabilize later this century at 9 to 10 billion). Unfortunately, the amount of soil available to meet these demands will not increase at all. In fact, the resource base is actually *shrinking* because of soil degradation and urbanization. Understanding how to better manage the soil resource is essential to our survival and to the maintenance of sufficient habitat for the other creatures that share this planet with us. In short, the study of soil science has never been more important than it is today.

1.1 WHAT ECOSYSTEM SERVICES DO SOILS PERFORM?

Scientists now recognize that the world's ecosystems provide goods and services estimated to be worth tens of trillions of dollars every year—as much as the gross national products (GNP) of all the world's economies (see Section 20.3). **Ecosystem services** can be thought of as:

- *provisioning* (providing goods such as water, food, medicines, lumber, etc.),
- *regulating* (processes that purify water, decompose wastes, control pests, or modify atmospheric gases),
- *supportive* (assisting with nutrient cycling, seed dispersal, primary biomass production, etc.) and
- *cultural* (providing spiritual uplift, scenic views, and outdoor recreation opportunities).

Over half of global ecosystem services arise on land, where soils play a major role.

Whether occurring in your backyard, a farm, a forest, or a regional watershed, soils have six key roles to play (Figure 1.2) in the provision of ecosystem services. *First*, soils support plant growth, by providing habitat for plant roots and nutrient elements for the entire plant. Soil properties often determine the nature of the vegetation present and, indirectly, the number and types of animals (including people) that the vegetation can support. *Second*, soils regulate water supplies. Water loss, utilization, contamination, and purification are all affected by

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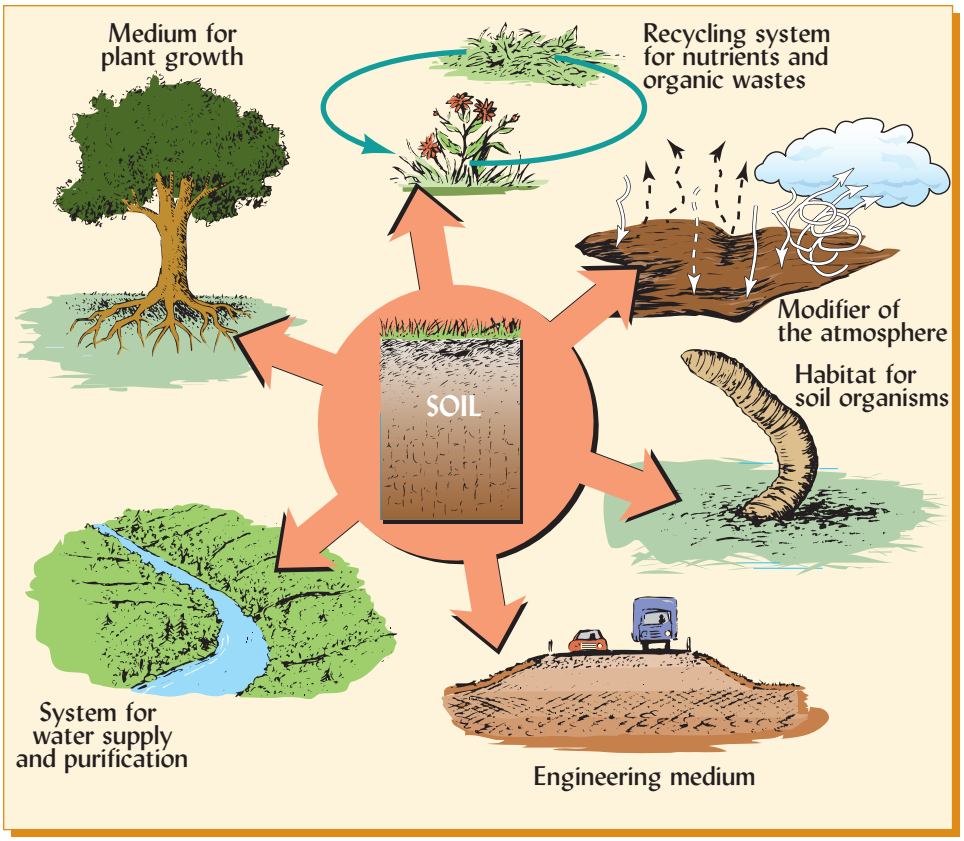

Figure 1.2 *The many functions and ecosystem services performed by soil can be grouped into six crucial ecological roles.* (Diagram courtesy of Ray R. Weil)

the soil. *Third*, the soil functions as nature's recycling system. Within the soil, waste products and dead bodies of plants, animals, and people are assimilated, and their basic elements are made available for reuse by the next generation of life. In addition to recycling, soil can serve as a protective covering of human artifacts for centuries before they are unearthed by archeologists. *Fourth*, soils are alive and are home to creatures from small mammals and reptiles to tiny insects to microorganisms of unimaginable numbers and diversity. *Fifth*, soils markedly influence the composition and physical condition of the atmosphere by taking up and releasing large quantities of carbon dioxide, oxygen, and other gases and by contributing dust and re-radiated heat energy to the air. *Finally*, soil plays an important role as an engineering medium. Soil is not only an important building material in the form of earth fill and bricks (baked soil material) but provides the foundation for virtually every road, airport, and house we build.

1.2 HOW DO SOILS SUPPORT PLANT GROWTH?

When we think of the forests, prairies, gardens, and fields that surround us, we usually envision the **shoots**—the plant leaves, flowers, stems, and limbs—forgetting that half of the plant world, the **roots**, exists belowground. Because plant roots are usually hidden from our view and difficult to study, we know much less about plant—environment interactions belowground than aboveground, but we must understand both to truly understand either. To begin with, let's list and then briefly discuss what a plant obtains from the soil in which its roots proliferate:

- Physical support
- Air
- Water
- Temperature moderation
- Protection from toxins
- Nutrient elements

First, the soil mass provides physical support, anchoring the root system so that the plant does not fall over or blow away. Occasionally, strong wind or heavy snow does topple a plant whose root system has been restricted by shallow or inhospitable soil conditions (Figure 1.3).

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Figure 1.3 *This wet, shallow soil failed to allow sufficiently deep roots to develop to prevent this tree from blowing over when snow-laden branches made it top-heavy during a winter storm.* (Photo courtesy of Ray R. Weil)

Because root respiration, like our own respiration, produces carbon dioxide (CO_2) and uses oxygen (O_2), an important function of the soil is ***ventilation***—maintaining the quantity and quality of air by allowing CO_2 to escape and fresh O_2 to enter the root zone. This ventilation is accomplished via networks of soil pores.

An equally important function of soil pores is to absorb water and hold it where it can be used by plant roots. As long as plant leaves are exposed to sunlight, the plant requires a continuous stream of water to use in cooling, nutrient transport, turgor maintenance, and photosynthesis. Since plants use water continuously, but in most places it rains only occasionally, the water-holding capacity of soils is essential for plant survival. A deep soil may store enough water to allow plants to survive long periods without rain (Figure 1.4).

The soil also moderates temperature fluctuations. Perhaps you can recall digging in garden soil (or even beach sand) on a summer afternoon and feeling how hot the soil was at the surface and how much cooler just a few centimeters below. The insulating properties of soil protect the deeper portion of the root system from extremes of hot and cold that often occur at

Figure 1.4 *A family of African elephants finds welcome shade under the leafy canopy of a huge acacia tree in this East African savanna. The photo was taken in a long dry season; no rain had fallen for almost five months. The tree roots are still using water from the previous rainy season stored several meters deep in the soil. The light-colored grasses are more shallow-rooted and have either set seed and died or gone into a dried-up, dormant condition.* (Photo courtesy of Ray R. Weil)

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the soil surface. For example, it is not unusual for the mid-afternoon temperature at the surface of bare soil to reach 40 °C, a condition lethal to most plant roots. Just a few centimeters deeper, however, the temperature may be 10 °C cooler, allowing roots to function normally.

Phytotoxic substances in soils may result from human activity (such as chemical spills or herbicide application), or they may be produced by plant roots, by microorganisms, or by natural chemical reactions. Many soil managers consider it a function of a good soil to protect plants from such substances by ventilating gases, by decomposing or adsorbing organic toxins, or by suppressing toxin-producing organisms. At the same time, it is true that some microorganisms in soil produce organic, growth-stimulating compounds. These substances, when taken up by plants in small amounts, may improve plant vigor.

A fertile soil will provide a continuing supply of dissolved **mineral nutrients** in amounts and relative proportions appropriate for optimal plant growth. These nutrients include such metallic elements as potassium, calcium, iron, and copper, as well as such nonmetallic elements as nitrogen, sulfur, phosphorus, and boron. Roots take these elements out of the soil solution and the plant incorporates most of them into the organic compounds that constitute its tissues. Animals usually obtain their mineral nutrients from the soil, indirectly, by eating plants. Under some circumstances, animals (including humans) satisfy their craving for minerals by ingesting soil directly (Figure 1.5 and Box 1.1). Plants also take up some elements that they do not appear to use, which is fortunate as animals do require several elements that plants do not (see periodic table, Appendix B).

Of the 92 naturally occurring chemical elements, 17 have been shown to be **essential elements**, meaning that plants cannot grow and complete their life cycles without them. Table 1.1 lists these and several additional elements that appear to be quasi-essential (needed by some but not all plants). Essential elements used by plants in relatively large amounts are called **macronutrients**; those used in smaller amounts are known as **micronutrients**. To remember the 17 essential elements, try this mnemonic device:

C.B. HOPKiNS CaFé—
Closed Monday Morning and Night—
See You Zoon, *the* ***Mg***

The bold letters indicate the chemical elements in this phrase; finding copper (Cu) and zinc (Zn) may require a bit of imagination.

In addition to the mineral nutrients just listed, plants may also use minute quantities of organic compounds from soils. However, uptake of these substances is not necessary for normal plant growth. The organic metabolites, enzymes, and structural compounds making up a plant's dry matter consist mainly of carbon, hydrogen, and oxygen, which the plant obtains by photosynthesis from air and water, not from the soil.

Plants *can* be grown in nutrient solutions without any soil (a method termed **hydroponics**), but then the plant-support functions of soils must be engineered into the system and maintained at a high cost of time, energy, and management. In fact, imagining the expense of attempting to grow enough for 7 billion people in hydroponic greenhouses is a

Figure 1.5 *A mountain goat (in Glacier National Park, USA) visits a natural* salt lick *where it ingests needed minerals directly from the soil. Animals normally obtain their dietary minerals indirectly from soils by eating plants.* (Photo courtesy of Ray R. Weil)

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BOX 1.1

DIRT FOR DINNER?[a]

You are probably thinking, "dirt (excuse me, *soil*) for dinner? Yuck!" Of course, various birds, reptiles, and mammals are well known to consume soil at special "licks," and involuntary, inadvertent ingestion of soil by humans (especially children) is widely recognized as a pathway for exposure to environmental toxins (see Chapter 18, Box 18.2), but many people, anthropologists and nutritionists included, find it hard to believe that anyone would *purposefully* ingest soil. Yet, research on the subject shows that many people do routinely eat soil, often in amounts of 20 to 100 g (up to $^1/_4$ pound) daily. **Geophagy** (deliberate "soil eating") is practiced in societies as disparate as those in Thailand, Turkey, rural Alabama, and urban Tanzania (Figure 1.6). Immigrants have brought the practice of soil eating to such cities as London and New York. In fact, scientists studying the practice suggest that geophagy is a widespread and normal human behavior. Children and women (especially when pregnant) appear more likely than men to be geophagists. Poor people eat soil more commonly than the relatively well-to-do.

People usually do not eat just any soil, but seek out particular soils, generally high in clay and low in sand, be it the hardened clay of a termite nest, the soft, white clay exposed in a riverbank, or the dark red clay from a certain deep soil layer. People in different places and circumstances seek to consume different types of soils—some seek sodium- or calcium-rich soils, others soil with high amounts of certain clays, still others seek soils rich in iron. Interestingly, unlike many other animals, humans rarely appear to eat soil to obtain salt. Possible benefits from eating soil may include mineral nutrient supplementation, although only iron appears to be sufficiently bioavailable to actually improve nutrition. While other mammals seem to obtain significant amounts of mineral nutrients from eating soil, the main benefit that humans receive is probably detoxification of ingested poisons and parasites (e.g., by adsorption to clay—see Chapter 8), relief from stomachaches, survival in times of famine, and psychological comfort. Geophagists have been known to go to great lengths to satisfy their cravings for soil. But before you run out and add some local soil to your menu, consider the potential downsides to geophagy. Aside from the possibly difficult task of developing a taste for the stuff, the drawbacks to eating soil (especially surface soils) can include parasitic worm infection, lead poisoning, and mineral nutrient imbalances (because of adsorption of some mineral nutrients and release of others)—as well as premature tooth wear!

Figure 1.6 *Bars of reddish clay soil sold for human consumption in a market in Morogoro, Tanzania. The soil bars (stacked neatly on the circular tray in foreground) are sold individually or by the bagful mainly to pregnant women, who commonly consume about 10 bars per day.* (Photo courtesy of Ray R. Weil)

[a]This box is largely based on a fascinating reviews by Young et al. (2011) and Abrahams (2012), (2005).

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Table 1.1
ELEMENTS NEEDED FOR PLANT GROWTH AND THEIR SOURCES[a]
The chemical forms most commonly taken in by plants are shown in parentheses, with the chemical symbol for the element in bold type.

Macronutrients: Used in relatively large amounts (>0.1% of dry plant tissue)		Micronutrients: Used in relatively small amounts (<0.1% of dry plant tissue)
Mostly from air and water	**Mostly from soil solids**	**From soil solids**
Carbon (**C**O_2)	*Cations:*	*Cations:*
Hydrogen (**H**$_2$O)	Calcium (**Ca**$^{2+}$)	Copper (**Cu**$^{2+}$)
Oxygen (**O**$_2$, H_2**O**)	Magnesium (**Mg**$^{2+}$)	*Cobalt (**Co**$^{2+}$)[b]
	Nitrogen (**N**H_4^+)	Iron (**Fe**$^{2+}$)
	Potassium (**K**$^+$)	Manganese (**Mn**$^{2+}$)
	Anions:	Nickel (**Ni**$^{2+}$)
	Nitrogen (**N**O_3^-)	*Sodium (**Na**$^+$)[b]
	Phosphorus (H_2**P**O_4^-, **H**PO_4^{2-})	Zinc (**Zn**$^{2+}$)
	Sulfur (**S**O_4^{2-})	*Anions:*
	*Silicon (H_4**Si**O_4, H_3**Si**O_4^-)[b]	Boron (H_3**B**O_3, H_4**B**O_4^-)
		Chlorine (**Cl**$^-$)
		Molybdenum (**Mo**O_4^{2-})

[a]Many other elements are taken up from soils by plants but are not *essential* for plant growth. Some of these (such as iodine, fluorine, barium, and strontium) do enhance the growth of certain plants, but do not appear to be absolutely required for normal growth, as are the 20 listed in this table. Still other elements (e.g., chromium, selenium, tin, and vanadium) are incorporated into plant tissues, where they may be used as essential mineral nutrients by humans and other animals, even though plants do not appear to require them. See periodic table in Appendix B.

[b]Elements marked by (*) are quasi-essential elements (*sensu*, Epstein and Bloom (2005)), required for some, but not for all, plants. Silicon is used in large amounts to play important roles in most plants, so is considered a plant-beneficial element, but has been proved essential only for diatoms and plants in the *Equisetaceae* family. Cobalt has been proved essential for only *Leguminosae* when in symbiosis with nitrogen-fixing bacteria (see Section 13.10). Sodium is essential in small amounts for plants using the C_4 photosynthesis pathway (mainly tropical grasses).

good way to comprehend the economic value of the food provision ecosystem service provided by soils. Thus, although hydroponic production is feasible for high-value plants on a small scale, production of the world's food and fiber and maintenance of natural ecosystems will always depend on millions of square kilometers of productive soils.

1.3 HOW DO SOILS REGULATE WATER SUPPLIES?

There is much concern about the quality and quantity of the water in our rivers, lakes, and underground aquifers. To maintain or improve water quality, we must recognize that nearly every drop of water in our rivers, lakes, estuaries, and aquifers has either traveled through the soil or flowed over its surface (excluding the relatively minor quantity of precipitation that falls directly into bodies of fresh surface water). Imagine, for example, a heavy rain falling on the hills surrounding the river in Figure 1.7. If the soil allows the rain to soak in, some of the water will be stored in the soil, some used by the trees, and some will seep slowly down through the soil layers to the groundwater, eventually entering the river over a period of months or years as **base flow**. As it soaks through the upper layers of soil, contaminated water is purified and cleansed by soil processes that remove many impurities and kill potential disease organisms.

Contrast the preceding scenario with what would occur if the soil were so shallow or impermeable that most of the rain could not penetrate the soil, but ran off the land surface, scouring surface soil and debris as it sped toward the river. The result would be a destructive flash flood of muddy contaminated water. This comparison highlights how the nature and

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Figure 1.7 *The condition of the soils covering these Blue Ridge foothills will greatly influence the quantity and quality of water flowing down the James River in Virginia, USA.* (Photo courtesy of Ray R. Weil)

management of soils in a watershed will influence the purity and amount of water finding its way to aquatic systems. For those who live in rural homes, the purifying action of the soil (in a septic drain field as described in Section 6.8) is the main barrier that stands between what flushes down the toilet and the water running into the kitchen sink!

1.4 HOW DO SOILS RECYCLE RAW MATERIALS?

What would a world be like without the recycling functions performed by soils? Without reuse of nutrients, plants and animals would have run out of nourishment long ago. The world would be covered with a layer, possibly hundreds of meters high, of plant and animal wastes and corpses. Obviously, recycling is vital to ecosystems, whether forests, farms, or cities. The soil system plays a pivotal role in the major geochemical cycles. Soils have the capacity to assimilate great quantities of organic waste, turning it into beneficial **soil organic matter**, converting the mineral nutrients in the waste to forms that can be utilized by plants and animals, and returning the carbon to the atmosphere as carbon dioxide, where it again will become a part of living organisms through plant photosynthesis. Some soils can accumulate large amounts of carbon as soil organic matter, thus reducing the concentration of atmospheric carbon dioxide and potentially mitigating global climate change (see Sections 1.5, 1.14, and 12.2).

1.5 HOW DO SOILS MODIFY THE ATMOSPHERE?

As the soil "breathes" in and out it interacts in many ways with the Earth's blanket of air. That is, soils absorb oxygen and other gases such as methane, while they release gases such as carbon dioxide and nitrous oxide. These gas exchanges between the soil and the atmosphere have a significant influence on atmospheric composition and global climate change. The evaporation of soil moisture is a major source of water vapor in the atmosphere, altering air temperature, composition, and weather patterns.

In places where the soil is dry, poorly structured, and unvegetated, soil particles can be picked up by winds and contribute great quantities of dust to the atmosphere, reducing visibility, increasing human health hazards from breathing dirty air, and altering the temperature of the air and of the Earth itself. Moist, well-vegetated, and structured soils can prevent such dust-laden air.

1.6 WHAT LIVES IN THE SOIL HABITAT?

When speaking of ecosystems needing protection, most people envision a stand of old-growth forest with its abundant wildlife, or an estuary with oyster beds and fisheries. Perhaps, once you have read this book, you will envision a handful of soil when someone speaks of an ecosystem.

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Figure 1.8 *The soil is home to a wide variety of organisms, both relatively large and very small. Here, a relatively large predator, a centipede (shown at about actual size), hunts for its next meal—which is likely to be one of the many smaller animals that feed on dead plant debris.* (Photo courtesy of Ray R. Weil)

Soil is not a mere pile of broken rock and dead debris. A handful of soil may be home to *billions* of organisms, belonging to thousands of species that act as predators, prey, producers, consumers, and parasites (Figure 1.8). This complex community of organisms influences human well-being through many ecosystem functions, but soils also influence human health directly, for good or for ill (see Box 1.2)

BOX 1.2

SOILS AND HUMAN HEALTH[a]

Although human health impacts of soils often go unrecognized, they affect us all for better and for worse. Soils impact our health indirectly via all six of the ecological soil functions described in Sections 1.2–1.7. Soils and soil components (such soil particles, mineral elements, and microorganisms) also directly affect our health when we come in contact with them by handling soil or in the food we eat, the water we drink, and the air we breathe.

THE FOOD WE EAT

The composition of our food reflects the nature of the soil in which it was grown. Zinc, which is involved in the function of hundreds of our body's enzymes, is a case in point; with insufficient dietary intake we may suffer such symptoms as hair loss and impairment of immune system function, fertility, and sex drive. About half of the world's agricultural soils are deficient in zinc, and about half of the world's people (largely in the same geographic areas) eat diets deficient in this micronutrient. Likewise, soils low in sulfur, as occur widely in Africa, Asia, Australia, and parts of North America, produce wheat (or beans, etc.) likely to be low in methionine and cystine, sulfur-containing amino acids essential for the human body to utilize the protein in food. Foods grown in certain areas tend to reflect the low levels of iodine and selenium in local soils, two elements not needed by plants but widely deficient as nutrients for people (causing goiters and Keshan disease, respectively). Other examples abound.

INFECTIOUS DISEASES FROM SOILS

Among the millions of soil-dwelling organisms, a few can bring disease and even death to humans. Among the more notorious soil pathogenic bacteria are *Clostridium tetani*, which causes tetanus and *Bacillus anthracis*, which causes anthrax and whose spores may survive in the soil for decades. Such soil-borne infectious bacterial diseases kill millions of people each year, including many babies and mothers who die during childbirth under unsanitary conditions. A less common, but still potentially fatal, soil-borne disease is caused when a soil fungus, *Blastomyces sp*, infects a cut in the skin or is breathed into the lungs. Blastomycosis is usually associated geographically with localized soil conditions, but it is hard to track down as its pneumonia-like lung symptoms or skin ulcerations may not appear for months after exposure. Cryptococcosis, a fairly rare disease causing brain damage or pneumonia-like lung symptoms, can be contracted by breathing in spores of *Cryptococcus*, another soil fungus. Still other human diseases are caused by microscopic soil animals, such round worms, hook worms, and

[a]Many scientific papers are available for further reading on soils and human health [see Alloway and Graham (2008); Frager et al. (2010); Griffin (2007); Liu and Khosla (2010); Stokes (2006)]. For research that illuminates why soil clays exhibit powers of healing (it's the metals adsorbed to the clays!), see Otto and Haydel (2013). For a review of human immune system regulation by soil (and other environmental) organisms, see Rook (2013).

(continued)

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BOX 1.2

SOILS AND HUMAN HEALTH *(CONTINUED)*

protozoa. An example of the latter is *Cryptosporidium sp.*, which cause widespread outbreaks of cryptosporidiosis, sometimes sickening (but rarely killing) thousands of people in a single city if the protozoa-containing soil or farm manure contaminates drinking water supplies. Another under-recognized health hazard comes from fine dust picked up by desert winds and carried halfway around the world (see Sections 2.2 and 17.2). Airborne dust not only poses a risk of physical irritation of lung tissues that results in cancer, but also carries pathogenic soil microorganisms that can remain alive and virulent during the intercontinental journey.

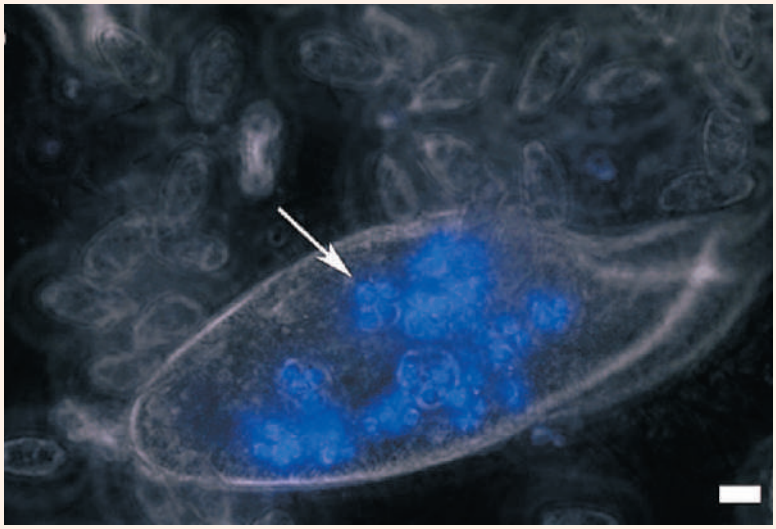

Figure 1.9 *Balance of nature in the soil ecosystem. This Paramecium, a single celled soil animal (protista) ingests and kills spores of the human pathogenic fungus Cryptococcus. Arrow shows spores inside the paramecium; white scale bar = 1μm. Microscopic image from Frager et al. (2010).*

THE CURATIVE POWERS OF SOILS

The aforementioned discussion does not mean that we should never hike in the forest or garden without rubber gloves (though gloves are a good idea if your hand has an open wound). To the contrary—the balance of nature in most soils is overwhelmingly in favor of organisms that provide ecosystem services essential to human welfare. For example, it was recently observed (Figure 1.9) that certain single-celled soil animals called *Paramecium*, voraciously eat the spores of the pathogenic fungus *Cryptococcus* just mentioned. In fact, soils play a far greater role in *curing* our diseases than in *causing* them!

Many people are unaware that plants grown in the soil are the source of most of the medicines (both traditional herbals and modern pharmaceuticals) that prevent, alleviate or cure so many of the diseases and ailments that plagued and often killed our ancestors. The story of Taxol (paclitaxel) illustrates this role quite well. This highly prized anticancer drug was first discovered in the bark of a rare type of yew tree that grows in the Pacific coast soils of Oregon and Washington States. Demand for this drug resulted in the destruction of half a million of these yews before scientists learned to make it from other organisms using molecular culture and gene-transfer techniques.

Soil microorganisms themselves are the source of most of our life-saving antibiotics Drugs such as penicillin, ciprofloxacin, and neomycin originate from certain soil bacteria (e.g., *Streptomyces*) and fungi (e.g., *Penicillium*) that produce these compounds as part of their defensive strategies against competing soil microbes. See Chapter 11 for more on soil microbes and their antibiotics. Poultices made from soil clays have long been effectively used in traditional medicine to heal skin conditions and fight infections. Some research even suggests that just being in close contact with healthy soils (think avid gardeners) and breathing in certain microorganisms or volatile compounds they produce may give people a sense of well-being through interactions with their brain chemistry (the marked increase in brain cell serotonin in response to the soil bacterium, *Mycobacterium vaccae*, is well documented). Regulation of our immune systems and promotion of our well-being by diverse soil microbes should be considered among the ecosystem services that soils provide.

We have said that billions of organisms made up of thousands of species can coexist in a handful of soil. How is it possible for such a diversity of organisms to live and interact in such a small space? One explanation is the tremendous range of niches and habitats that exist in even a uniform-appearing soil. Some pores of the soil will be filled with water in which organisms such as roundworms, diatoms, rotifers, and bacteria swim. Tiny insects and mites may be crawling about in other larger pores filled with moist air. Micro-zones of good aeration may be only millimeters from areas of **anoxic** conditions. Different areas may be enriched with decaying organic materials; some places may be highly acidic, some more basic. Temperature, too, may vary widely.

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Hidden from view in the world's soils are communities of living organisms every bit as complex and intrinsically valuable as their larger counterparts that roam the savannas, forests, and oceans of the Earth. In fact, soils harbor a large part of the Earth's genetic diversity. Soils, like air and water, are important components of larger ecosystems. So it is important to assure that **soil quality** is considered, along with air quality and water quality, in discussions of environmental protection.

1.7 SOIL AS AN ENGINEERING MEDIUM

Soil is one of the earliest and the most widely used of building materials. Nearly half the people in the world live in houses constructed from soil. Soil buildings vary from traditional African mud huts to large centuries-old circular apartment houses in China (Figure 1.10) to today's environmentally-friendly "rammed-earth" buildings (see http://www.yourhome.gov.au/materials/rammed-earth).

"*Terra firma*, solid ground." We usually think of the soil as being firm and solid, a good base on which to build roads and all kinds of structures. Indeed, most constructed structures do rest on the soil, and many construction projects require excavation into the soil. Unfortunately, as can be seen in Figure 1.11, some soils are not as stable as others. Reliable construction on soils, and with soil materials, requires knowledge of the diversity of soil properties, as discussed in this and later chapters. Designs for roadbeds or building foundations that work well in one location on one type of soil may be inappropriate for another location with different soils.

Working with natural soils or excavated soil materials is not like working with concrete or steel. Properties such as bearing strength, compressibility, shear strength, and stability are much more variable and difficult to predict for soils than for manufactured building materials. Chapter 4 provides an introduction to some engineering properties of soils. Many other physical properties discussed will have direct application to engineering uses of soil. For example, Chapter 8 discusses properties of certain types of clay soils that upon wetting expand with sufficient force to crack foundations and buckle pavements. Much of the information on soil properties and soil classification discussed in later chapters will be of great value to people planning land uses that involve construction or excavation.

Figure 1.10 *Soil is among the oldest and most common of building materials, with half the world's people living in homes made of soil.* (left) *An elderly African villager weaves a basket outside his house made from red and black clay soil reinforced with small tree branches (a technique termed wattle and daub).* (right) *Several round* Tulou *apartment buildings housing up to 80 families each in Fu-Jian, China. These buildings have 2-m-thick walls made thousands of years ago from compacted yellowish soil mixed with bamboo and stones. These massive "rammed earth" walls make the buildings warm in winter but cool in summer (see Chapter 7) and resistant to damage from earthquakes.* (Left photo courtesy of Ray R. Weil; right photo courtesy of Lu Zhang, Zhejiang, China)

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Figure 1.11 *Better knowledge of the soils on which this road was built may have allowed its engineers to develop a more stable design, thus avoiding this costly and dangerous situation.* (Photo courtesy of Ray R. Weil)

1.8 THE PEDOSPHERE AND THE CRITICAL ZONE?[2]

The outer layers of our planet that lie between the tops of the tallest trees and the bottom of the groundwater aquifers that feed our rivers comprise what scientists term ***The Critical Zone***. Environmental research is increasingly focused on this zone where active cycles and flows of materials and energy support life on Earth. The soil plays a central role in this critical zone. The importance of the soil derives in large part from its role as an **interface** between the worlds of rock (the **lithosphere**), air (the **atmosphere**), water (the **hydrosphere**), and living things (the **biosphere**). Environments where all four of these worlds interact are often the most complex and productive on Earth. An estuary, where shallow waters meet the land and air, is an example of such an environment. The soil, or **pedosphere**, is another example (Figure 1.12).

The concept of the soil as interface means different things at different scales. At the scale of kilometers (Figure 1.12*a*), soils channel water from rain to rivers and transfer mineral elements from bed rocks to the oceans. They also substantially influence the global balance of atmospheric gases. At a scale of a few meters (Figure 1.12*b*), soil forms the transition zone between hard rock and air, holding both liquid water and oxygen gas for use by plant roots. It transfers mineral elements from the Earth's rock crust to its vegetation. It processes or stores the organic remains of terrestrial plants and animals. At a scale of a few millimeters (Figure 1.12*c*), soil provides diverse micro-habitats for air-breathing and aquatic organisms, channels water and nutrients to plant roots, and provides surfaces and solution vessels for thousands of biochemical reactions. Finally, at the scale of a few micrometers or nanometers (Figure 1.12*d*), soil provides ordered and complex surfaces, both mineral and organic, that act as templates for chemical reactions and interact with water and solutes. Its tiniest mineral particles form micro-zones of electromagnetic charge that attract everything from bacterial cell walls to proteins to conglomerates of water molecules. As you read the entirety of this book, the frequent cross-referencing between one chapter and another will remind you of the importance of scale and interfacing to the story of soil.

1.9 SOILS AS NATURAL BODIES

You may notice that this book sometimes refers to "soil," sometimes to "the soil," sometimes to "a soil," and sometimes to "soils." These variations of the word "soil" refer to two distinct concepts—*soil* as a material or *soils* as natural bodies. *Soil* is a material composed of minerals, gases, water, organic substances, and microorganisms. Some people (usually *not* soil scientists!)

[2]For a readable introduction to the concept of the Critical Zone, see Fisher (2012).

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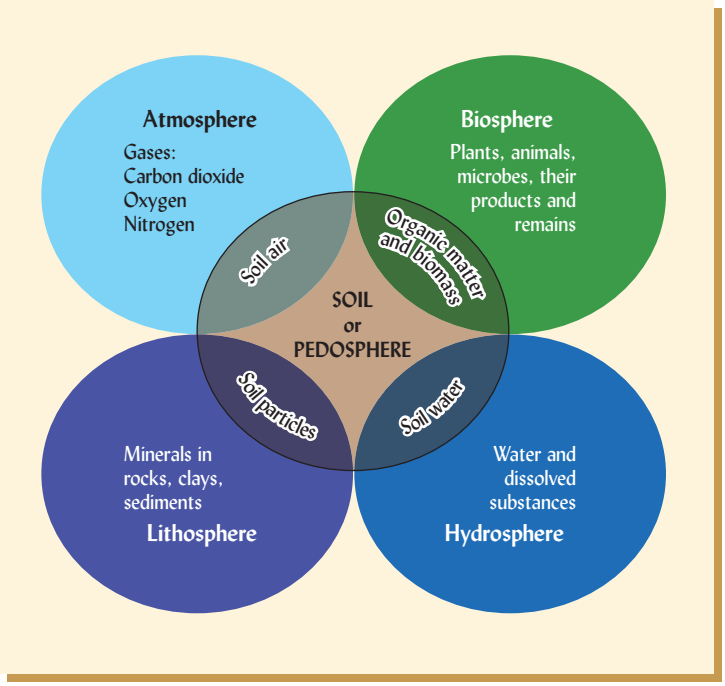
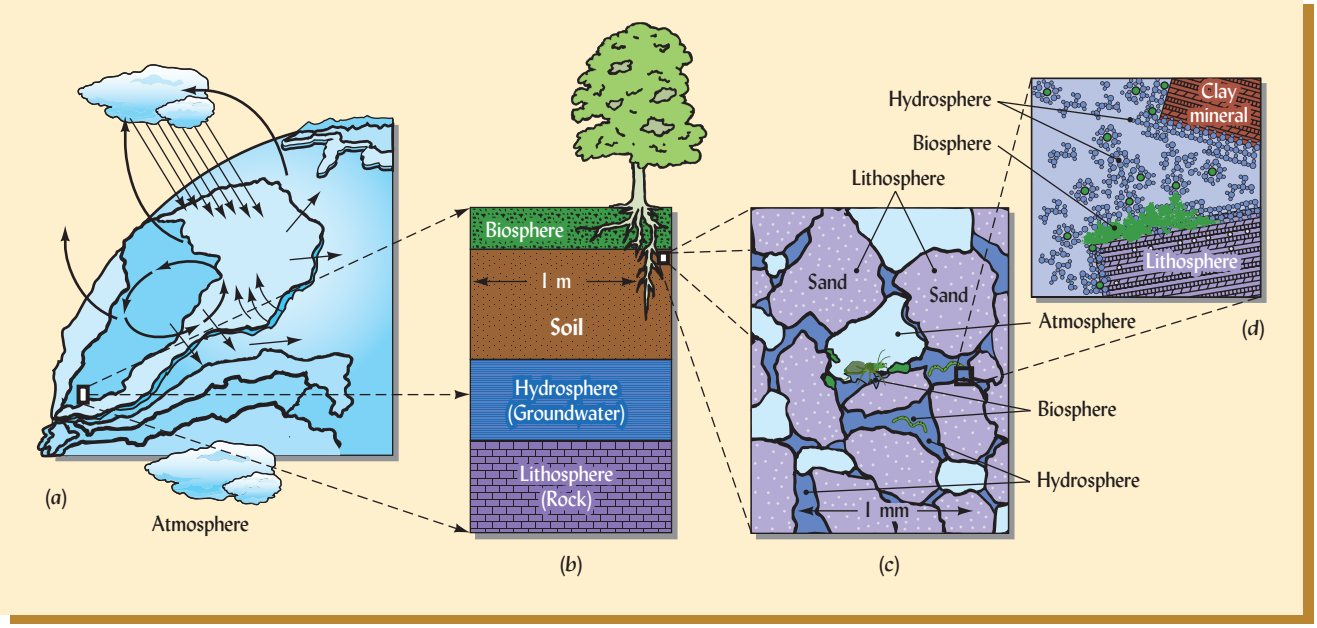


Figure 1.12 *The pedosphere, where the worlds of rock (the lithosphere), air (the atmosphere), water (the hydrosphere), and life (the biosphere) all meet. The soil as interface can be understood at many different scales. At the kilometer scale* (a), *soil participates in global cycles of rock weathering, atmospheric gas changes, water storage and partitioning, and the life of terrestrial ecosystems. At the meter scale* (b), *soil forms a transition zone between the hard rock below and the atmosphere above—a zone through which surface water and groundwater flow and in which plants and other living organisms thrive. A thousand times smaller, at the millimeter scale* (c), *mineral particles form the skeleton of the soil that defines pore spaces, some filled with air and some with water, in which tiny creatures lead their lives. Finally, at the micrometer and nanometer scales* (d), *soil minerals (lithosphere) provide charges, reactive surfaces that adsorb water and cations dissolved in water (hydrosphere), gases (atmosphere), and bacteria and complex humus macromolecules (biosphere).* (Diagram courtesy of Ray R. Weil)



also refer to this material as *dirt*, especially when it is found where it is not welcome (e.g., in your clothes or under your fingernails).

A soil is a three-dimensional natural body in the same sense that a mountain, lake, or valley is. *The soil* is a collection of individually different soil bodies, often said to cover the land as the peel covers an orange. However, while the peel is relatively uniform around the orange, the soil is highly variable from place to place on Earth. One of the individual bodies, *a soil*, is to *the soil* as an individual tree is to the Earth's vegetation. Just as one may find sugar maples, oaks, hemlocks, and many other species of trees in a particular forest, so, too, might one find Los Osos loams, Altamont clays, San Benito clay loams, Diablo silty clays, and other kinds of soils in a particular landscape.

Soils are natural bodies composed of soil (the material just described) *plus* roots, animals, rocks, artifacts, and so forth. By dipping a bucket into a lake you may sample some of its water. In the same way, by making a hole in a soil, you may retrieve some soil. Thus, you can

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take a sample of soil or water into a laboratory and analyze its contents, but you must go out into the field to study a soil or a lake.

In most places, the rock exposed at the Earth's surface has crumbled and decayed to produce a layer of unconsolidated debris overlying the hard, unweathered rock. This unconsolidated layer is called the ***regolith*** (Figure 1.13) and varies in thickness from virtually nonexistent in some places (i.e., exposed bare rock) to tens of meters in other places. Where the underlying rock has weathered in place to the degree that it is loose enough to be dug with a spade, the term **saprolite** is used. In other cases, regolith materials have been transported many kilometers from the site of its initial formation and then deposited over the bedrock which it now covers. Thus, regolith material may or may not be related to the rock now found below it.

Through their biochemical and physical effects, living organisms such as bacteria, fungi, and plant roots have altered the upper part—and, in many cases, the entire depth—of the regolith. Here, at the interface between the worlds of rock, air, water, and living things, soil is born. The transformation of inorganic rock and debris into a living soil is one of nature's most fascinating displays. Although generally hidden from everyday view, the soil and regolith can often be seen in road cuts and other excavations.

A soil is the product of both destructive and creative (synthetic) processes. Weathering of rock and microbial decay of organic residues are examples of destructive processes, whereas the formation of new minerals and new stable organic-mineral complexes are examples of synthesis. Perhaps the most striking result of synthetic processes is the formation of contrasting layers called **soil horizons**. The development of these horizons in the upper regolith is a unique characteristic of soil that sets it apart from the deeper regolith materials (Figure 1.13).

Soil scientists specializing in **pedology** (*pedologists*) study soils as natural bodies, the properties of soil horizons, and the relationships among soils within a landscape. Other soil scientists, called **edaphologists**, focus on the soil as habitat for living things, especially for

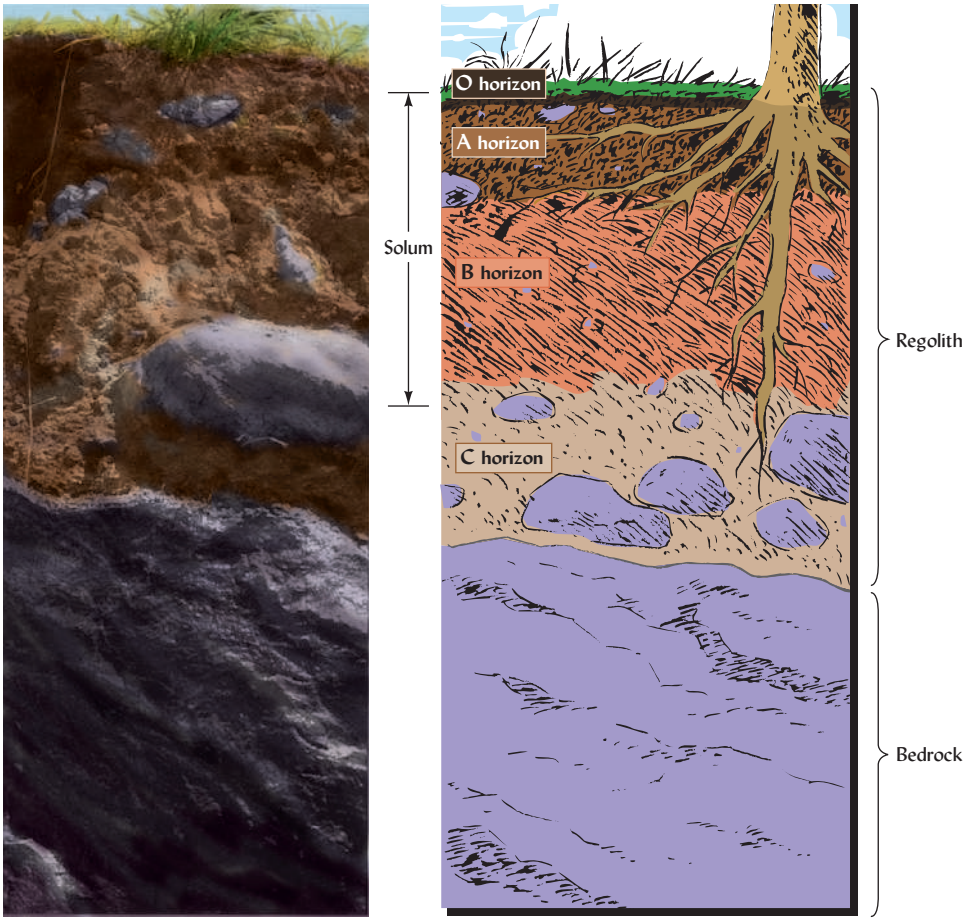

Figure 1.13 *Relative positions of the regolith, its soil, and the underlying bedrock. Note that the soil is a part of the regolith and that the A and B horizons are part of the* solum *(from the Latin word* solum, *which means soil or land). The C horizon is the part of the regolith that underlies the solum but may be slowly changing into soil in its upper parts. Sometimes the regolith is so thin that it has been changed entirely to soil; in such a case, soil rests directly on the bedrock.*
(Photo courtesy of Ray R. Weil)

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plants. For both types of study it is essential to examine soils at all scales and in all three dimensions (especially the vertical dimension).

1.10 THE SOIL PROFILE AND ITS LAYERS (HORIZONS)

Soil scientists often dig a large hole, called a *soil pit* (e.g. Figure 19.6), usually several meters deep and about a meter wide, to expose soil horizons for study. The vertical section exposing a set of horizons in the wall of such a pit is termed a ***soil profile***. Road cuts and other ready-made excavations can expose soil profiles and serve as windows to the soil. In an excavation open for some time, horizons may be more clearly seen if a fresh face is exposed by scraping off a layer of material several centimeters thick from the pit wall. Observing how soils exposed in road cuts vary from place to place can add a fascinating new dimension to travel. Once you have learned to interpret the different horizons (see Chapter 2), soil profiles tell you much about the environment and history of a region as well as warn you about potential problems in using the land.

Horizons within a soil may vary in thickness and have somewhat irregular boundaries, but generally they parallel the land surface (Figure 1.14). This alignment is expected since the differentiation of the regolith into distinct horizons is largely the result of influences such as air, water, solar radiation, and plant material, originating at the soil–atmosphere interface. Because the weathering of the regolith occurs first at the surface and works its way down, the uppermost layers have been changed the most, while the deepest layers are most similar to the original regolith, which is referred to as the soil's ***parent material***. In places where the regolith was originally rather uniform in composition, the material below the soil may have a similar composition to the parent material from which the soil formed. In other cases, the regolith

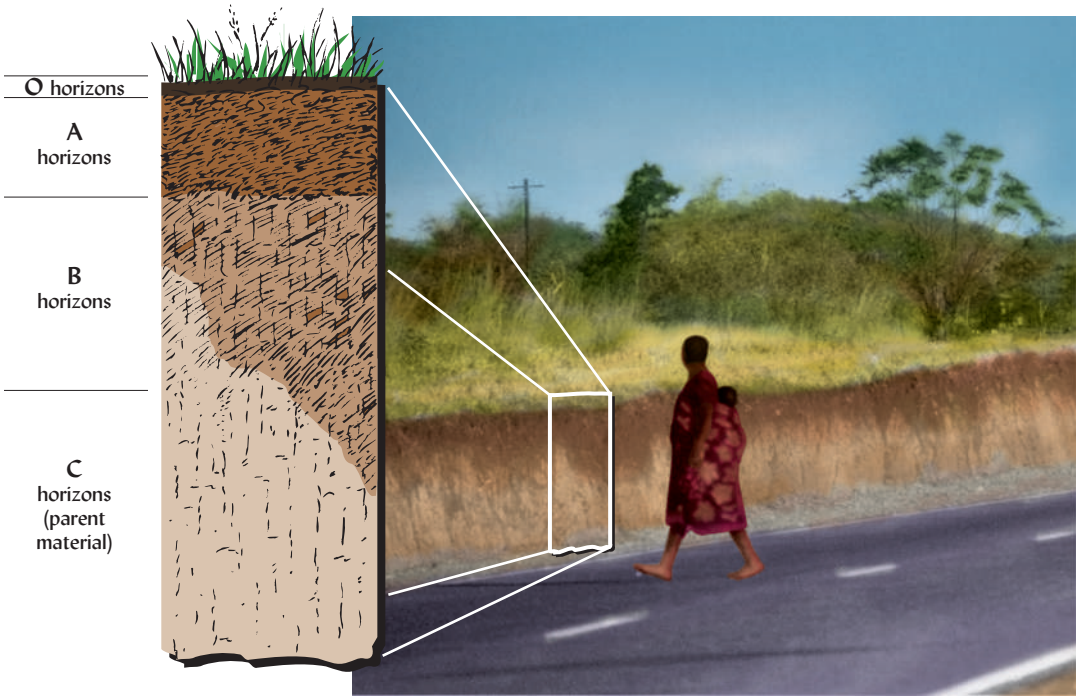

Figure 1.14 *This road cut in central Africa reveals soil layers or horizons that parallel the land surface. Taken together, these horizons comprise the profile of this soil, as shown in the enlarged diagram. The surface litter or O horizon may be very thin or nonexistent under this type of vegetation. The upper horizons are designated* A horizons. *They are usually higher in organic matter and darker in color than the lower horizons. Some constituents, such as iron oxides and clays, have been moved downward from the A horizons by percolating rainwater. The lower horizon, called a* B horizon, *is sometimes a zone in which clays and iron oxides have accumulated, and in which distinctive structure has formed. The presence and characteristics of the horizons in this profile distinguish this soil from the thousands of other soils in the world.* (Photo courtesy of Ray R. Weil)

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material has been transported by wind, water, or glaciers and deposited on top of dissimilar material. In such a case, the regolith material found below a soil may be quite different from the upper layer of regolith in which the soil is formed.

In undisturbed ecosystems, especially forests, organic remains of fallen leaves and other plant and animal materials tend to accumulate on the surface. There they undergo varying degrees of physical and biochemical breakdown and transformation so that layers of older, partially decomposed materials may underlie the freshly added debris. Together, these organic layers at the soil surface are designated the ***O horizons*** (Figure 1.15).

Soil animals and percolating water move some of these organic materials downward to intermingle with the mineral grains of the regolith. These join the decomposing remains of plant roots to form organic materials that darken the upper mineral layers. Also, because weathering tends to be most intense nearest the soil surface, in many soils the upper layers lose

Figure 1.15 *A piece of the O horizon from a deciduous forest floor in Vermont, USA.* (Photo courtesy of Ray R. Weil)

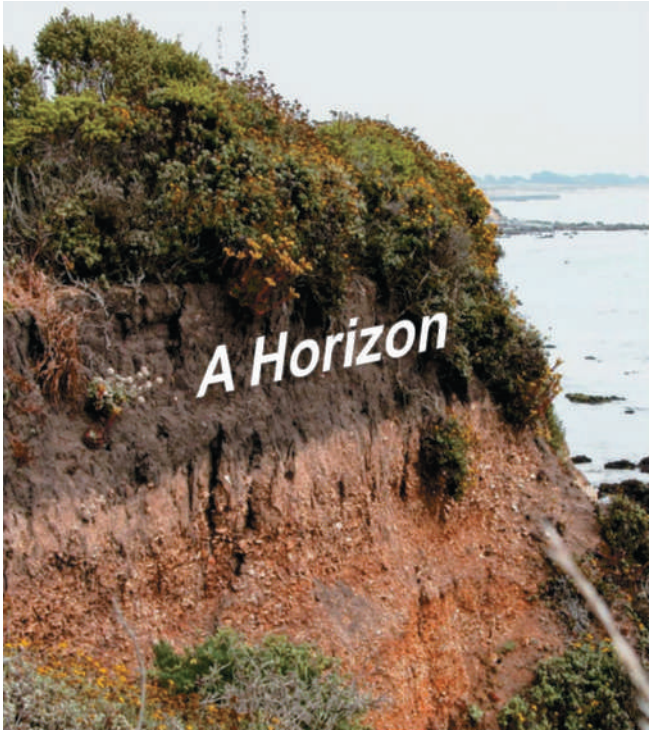

Figure 1.16 *Decaying plant materials have darkened a thick A horizon that caps this soils along the central California coast in the United States.* (Photo courtesy of Ray R. Weil)

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some of their clay or other weathering products by leaching to the horizons below. ***A horizons*** are the layers nearest the surface that are dominated by mineral particles but have been darkened by the accumulation of organic matter (Figure 1.16).

In some soils, intensely weathered and leached horizons that have not accumulated organic matter occur in the upper part of the profile, usually just below the A horizons. These horizons are designated ***E horizons*** (Figures 1.17 and 1.18).

The layers underlying the A and O horizons contain comparatively less organic matter than the horizons nearer the surface. Varying amounts of silicate clays, iron and aluminum oxides, gypsum, or calcium carbonate may accumulate in the underlying horizons. The accumulated materials may have been washed down from the horizons above, or they may have been formed in place through the weathering process. These underlying layers are referred to as ***B horizons*** (Figure 1.18).

Plant roots and microorganisms often extend below the B horizon, especially in humid regions, causing chemical changes in the soil water, some biochemical weathering of the regolith, and the formation of ***C horizons***. The C horizons are the least weathered part of the soil profile.

In some soil profiles, the component horizons are very distinct in color, with sharp boundaries that can be seen easily by even novice observers. In other soils, the color changes between horizons may be very gradual, and the boundaries more difficult to locate. However, color is only one of many properties by which one horizon may be distinguished from the horizon above or below it (see Figure 1.18). The study of soils in the field is often quite a sensual activity that requires all the senses to delineate the horizons present. In addition to seeing the

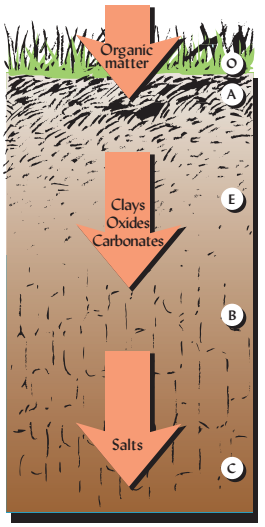

Figure 1.17 *Horizons begin to differentiate as materials are added to the upper part of the profile and other materials are translocated to deeper zones. Under certain conditions, usually associated with forest vegetation and high rainfall, a leached E horizon forms between organic matter-rich A and the B horizons. If sufficient rainfall occurs, soluble salts will be carried below the soil profile, perhaps all the way to the groundwater. Many soils (e.g., the soil in Figure 1.14) lack one or more of the five horizons shown here.* (Diagram courtesy of Ray R. Weil)

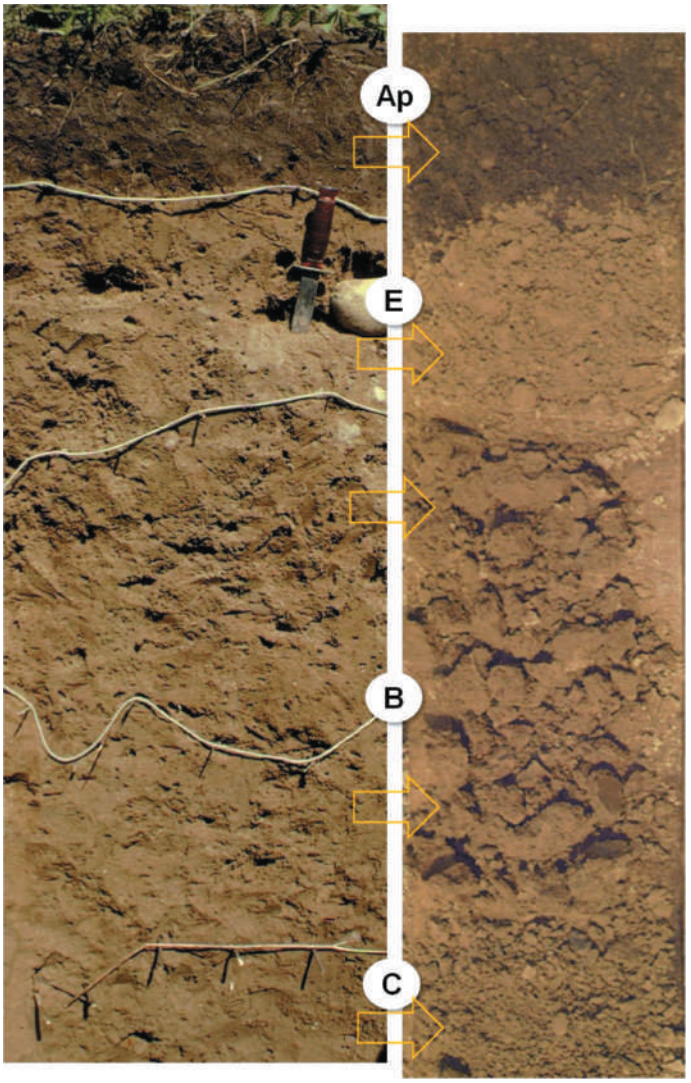

Figure 1.18 (Left) *This soil profile was exposed by digging a pit about 2 meters deep in a well-developed soil (a Hapludalf) in southern Michigan, USA. The top horizon can be easily distinguished because it has a darker color than those below it. However, some of the horizons in this profile are difficult to discern on the basis of color differences, especially in a photo. The white string was attached to the profile to clearly demarcate some of the horizon boundaries. Then a trowel full of soil material was removed from each horizon and placed on a board, at right. It is clear from the way the soil either crumbled or held together that soil material from horizons with very similar colors may have very different physical properties.* (Photos courtesy of Ray R. Weil)

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colors in a profile, a soil scientist may feel, smell, and listen[3] to the soil, as well as conduct chemical tests, in order to distinguish the horizons present.

1.11 TOPSOIL AND SUBSOIL

The organically enriched A horizon at the soil surface is sometimes referred to as ***topsoil***. Plowing and cultivating a soil homogenizes and modifies the upper 10 to 25 cm of the profile to form a plow layer. The plow layer may remain long after cultivation has ceased. For example, a forest in the New England area of the US that has regrown on abandoned farmland, you may still see the smooth boundary between the century-old plowed layer and the lighter-colored, undisturbed soil below.

In cultivated soils, the majority of plant roots can be found in the topsoil as that is the zone in which the cultivator can most readily enhance the supply of nutrients, air, and water by mixing in organic and inorganic amendments, loosening the structure, and applying irrigation. Sometimes the plow layer is removed from a soil and sold as topsoil for use at another site. This use of topsoil is especially common to provide a rooting medium suitable for lawns and shrubs around newly constructed buildings, where the original topsoil was removed or buried and the underlying soil layers were exposed during grading operations (Figure 1.19).

The soil layers that underlie the topsoil are referred to as ***subsoil***. Although usually hidden from view, the subsoil horizons can greatly influence most land uses. Much of the water needed by plants is stored in the subsoil. Many subsoils also supply important quantities of certain plant nutrients. The properties of the topsoil are commonly far more conducive to plant growth than those of the subsoil. In cultivated soils, therefore, productivity is often

Figure 1.19 *The large gray-brown mound of material in the foreground at this construction site consists of topsoil (A horizon material) carefully separated from the lower horizons and pushed aside during initial grading operations. Behind it is a similar sized pile of reddish-brown soil from the lower (subsoil) horizons. The stockpiles were then seeded with grasses to protect from erosion. The subsoil material will be used during construction to fill in low spots and build foundations and roadbeds. After construction activities are complete, the stockpiled topsoil (front pile) will be used in landscaping the grounds around the new buildings.* (Photo courtesy of Ray R. Weil)

[3]For example, the grinding sound emitted by wet soil rubbed between one's fingers indicates a sandy nature.

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correlated with the thickness of the topsoil layer. Subsoil layers that are too dense, acidic, or wet can impede root growth. It may be extremely difficult and expensive to physically or chemically modify the subsoil.

Many of the chemical, biological, and physical processes that occur in the upper soil layers also take place to some degree in the C horizons, which may extend deep into the underlying saprolite or other regolith material. Traditionally, the lower boundary of the soil has been considered to occur at the greatest rooting depth of the natural vegetation, but soil scientists are increasingly studying layers below this in order to understand ecological processes of the critical zone such as groundwater pollution, parent material weathering, and biogeochemical cycles (Box 1.3).

BOX 1.3

USING INFORMATION FROM THE ENTIRE SOIL PROFILE

Soils are three-dimensional bodies that carry out important ecosystem processes at all depths in their profiles. Depending on the particular application, the relevant information may come from soil layers as shallow as the upper 1 or 2 cm or as deep as the lowest layers of saprolite (Figure 1.20).

For example, the upper few centimeters of soil often hold the keys to plant growth and biological diversity, as well as to certain hydrologic processes. Here, at the interface between the soil and the atmosphere, living things are most numerous and diverse. Forest trees largely depend for nutrient uptake on a dense mat of fine roots growing in this zone. The physical condition of this thin surface layer may also determine whether rain will soak in or run downhill on the land surface. Certain pollutants, such as lead, are also concentrated in this zone. For many types of soil investigations it will be necessary to sample the upper few centimeters separately so that important conditions are not overlooked.

On the other hand, it is equally important not to confine one's attention to the easily accessible "topsoil," for many soil properties are to be discovered only in the deeper layers. Plant-growth problems are often related to inhospitable conditions in the B or C horizons that restrict the penetration of roots. Similarly, the great volume of these deeper layers may control the amount of plant-available water held by a soil. For the purposes of recognizing or mapping different types of soils, the properties of the B horizons are often paramount. Not only is this the zone of major accumulations of minerals and clays, but the layers nearer the soil surface may be too quickly altered by management and soil erosion to be considered a reliable basis for soil classification.

In deeply weathered regoliths, the lower C horizons and saprolite play important roles. These layers, generally at depths below 1 or 2 meters and often as deep as 5 to 10 meters, greatly affect the suitability of soils for most urban uses that involve construction or excavation. The proper functioning of on-site sewage disposal systems and the stability of building foundations are often determined by regolith properties at these depths. Likewise, processes that control the movement of pollutants to groundwater or the weathering of geologic materials may occur at depths of many meters. These deep layers also have major ecological influences because, although the intensity of biological activity and plant rooting may be quite low, the total impact can be great as a result of the enormous volume of soil that may be involved. This is especially true of forest systems in warm climates.

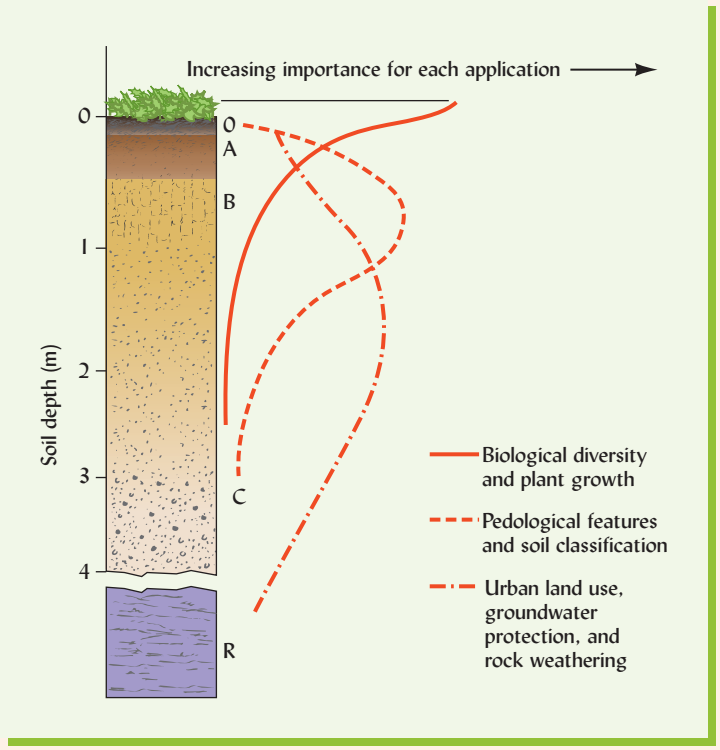

Figure 1.20 *Information important to different soil functions and applications is most likely to be obtained by studying different layers of the soil profile.* (Diagram courtesy of Ray R. Weil)

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1.12 SOIL—INTERFACE OF AIR, MINERALS, WATER, AND LIFE

The relative proportions of air, water, mineral matter, and organic matter greatly influence the behavior and productivity of soils. In a soil, these four components are mixed in complex patterns. Figure 1.21 shows the approximate proportions (by volume) of the components found in a **loam** surface soil in good condition for plant growth. Although a handful of soil may at first seem to be a solid thing, it should be noted that only about half the soil volume consists of solid material (mineral and organic); the other half consists of pore spaces filled with air or water. Of the solid material, typically most is mineral matter derived from the rocks of the Earth's crust. Only about 5% of the *volume* in this ideal soil consists of organic matter. Since it is far less dense than mineral matter, the organic matter accounts for only about 2% of the *weight* of this soil. However, the influence of the organic component on soil properties is often far greater than these small proportions would suggest.

The spaces between the particles of solid material are just as important to the nature of a soil as are the particles themselves. Soils with much more than 50% of their volume in solids are likely to be too compacted for good plant growth. It is in these pore spaces that air and water circulate, roots grow, and microscopic creatures live. Plant roots need both air and water. In an optimum condition for most plants, the pore space will be divided roughly equally among the two, with 25% of the soil volume consisting of water and 25% consisting of air. If there is much more water than this, the soil will be waterlogged. If much less water is present, plants will suffer from drought. The relative proportions of water and air fluctuate as water is added or lost. Compared to surface soil layers, subsoils tend to contain less organic matter, less total pore space, and a larger proportion of its pore space is made up of small pores (*micropores*), which tend to be filled with water rather than with air.

1.13 WHAT ARE THE MINERAL (INORGANIC) CONSTITUENTS OF SOILS?

Except in organic soils, most of the soil's solid framework consists of **mineral**[4] particles. The larger soil particles (stones, gravel, and coarse sands) are generally rock fragments consisting of several different minerals. Smaller particles tend to be made of a single mineral.

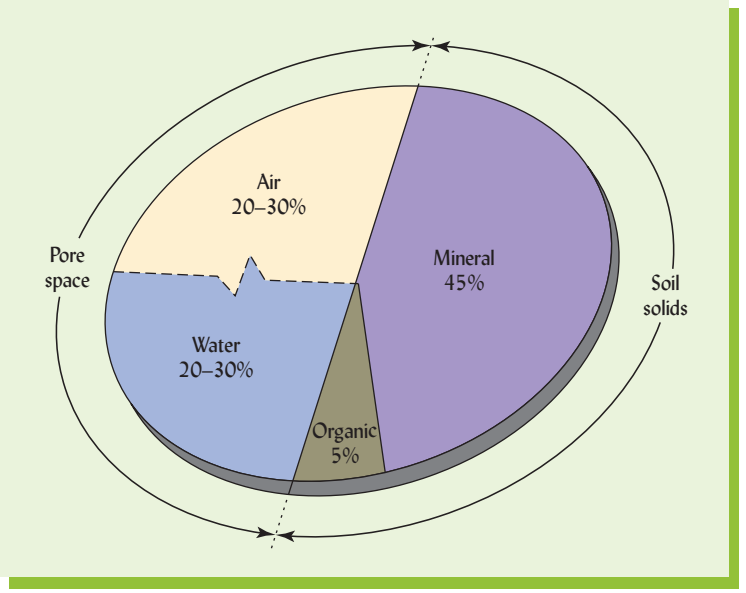

Figure 1.21 *Volume composition of a loam surface soil when conditions are good for plant growth. The broken line between water and air indicates that the proportions of these two components fluctuate as the soil becomes wetter or drier. Nonetheless, a nearly equal proportion of air and water is generally ideal for plant growth.*

[4]The word *mineral* is used in soil science in three ways: (1) as a general adjective to describe inorganic materials derived from rocks; (2) as a specific noun to refer to distinct minerals found in nature such as quartz and feldspars (see Chapter 2 for detailed discussions of soil-forming minerals and the rocks in which they are found); and (3) as an adjective to describe chemical elements, such as nitrogen and phosphorus, in their inorganic state in contrast to their occurrence as part of organic compounds.

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Excluding, for the moment, the larger rock fragments such as stones and gravel, soil particles range in size over four orders of magnitude: from 2.0 millimeters (mm) to smaller than 0.0002 mm in diameter (Table 1.2). **Sand** particles are large enough (2.0–0.05 mm) to be seen by the naked eye and feel gritty when rubbed between the fingers. Sand particles do not adhere to one another; therefore, sands do not feel sticky. **Silt** particles (0.05–0.002 mm) are too small to be seen without a microscope or to be felt individually, so silt feels smooth but not sticky, even when wet. **Clay** particles are the smallest mineral particles (<0.002 mm) and adhere together to form a sticky mass when wet and hard clods when dry. The smaller particles (<0.001 mm) of clay (and similar-sized organic particles) have **colloidal**[5] properties and can be seen only with the aid of an electron microscope. Because of their extremely small size, colloidal particles possess a tremendous amount of surface area per unit of mass. The surfaces of soil colloids (both mineral and organic) exhibit electromagnetic charges that attract positive and negative ions as well as water, making this fraction of the soil the most chemically and physically active (see Chapter 8).

Soil Texture

The proportion of particles in these different size ranges is described by **soil texture**. Terms such as *sandy loam*, *silty clay*, and *clay loam* are used to identify the soil texture. Texture has a profound influence on many soil properties, and it affects the suitability of a soil for most uses. To understand the degree to which soil properties can be influenced by texture, imagine sunbathing first on a sandy beach (loose sand) and then on a clayey beach (sticky mud). The difference in these two experiences would be due largely to the properties described in Table 1.2.

To anticipate the effect of clay on the way a soil will behave, it is necessary to know the *kinds* of clays as well as the *amount* present. As home builders and highway engineers know all too well, certain clayey soils, such as those high in smectite clays, make very unstable material on which to build because they swell when wet and shrink when dry. This shrink–swell action can easily crack foundations and cause retaining walls to collapse. These clays also become extremely sticky and difficult to work with when they are wet. Other types of clays, formed under different conditions, can be very stable and easy to work with. Learning about the different types of clay minerals will help us understand many of the physical and chemical differences among soils in various parts of the world (see Box 1.4).

Table 1.2
Some General Properties of the Three Major Size Classes of Inorganic Soil Particles

	Property	Sand	Silt	Clay
1.	Range of particle diameters in millimeters	2.0–0.05	0.05–0.002	Smaller than 0.002
2.	Means of observation	Naked eye	Microscope	Electron microscope
3.	Dominant minerals	Primary	Primary and secondary	Secondary
4.	Attraction of particles for each other	Low	Medium	High
5.	Attraction of particles for water	Low	Medium	High
6.	Ability to hold chemicals and nutrients in plant-available form	Very low	Low	High
7.	Consistency when wet	Loose, gritty	Smooth	Sticky, malleable
8.	Consistency when dry	Very loose, gritty	Powdery, some clods	Hard clods

[5]Colloidal systems are two-phase systems in which very small particles of one substance are dispersed in a medium of a different substance. Clay and organic soil particles smaller than about 0.001 mm (1 micrometer, μm) in diameter are generally considered to be colloidal in size. Milk and blood are other examples of colloidal systems in which very small solid particles are dispersed in a liquid medium.

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BOX 1.4

OBSERVING SOILS IN DAILY LIFE

Your study of soils can be enriched if you make an effort to become aware of the many daily encounters with soils and their influences that go unnoticed by most people. When you dig a hole to plant a tree or set a fence post, note the different layers encountered, and note how the soil from each layer looks and feels. If you pass a construction site, take a moment to observe the horizons exposed by the excavations. An airplane trip is a great opportunity to observe how soils vary across landscapes and climatic zones. If you are flying during daylight hours, ask for a window seat on the side away from the sun. Look for the shapes or divisions between individual soils in plowed fields if you are flying over agricultural land near the beginning of the growing season (Figure 1.22).

Soils can give you clues to understanding the natural processes going on around you. Down by the stream, use a magnifying glass to examine the sand deposited on the banks or bottom. It may contain minerals not found in local rocks and soils but originating many kilometers upstream. When you wash your car, see if the mud clinging to the tires and fenders is of a different color or consistency than the soils near your home. Does the "dirt" on your car tell you where you have been driving? Other examples of soil hints can be found even closer to home. The next time you bring home celery or leaf lettuce from the supermarket, look carefully for bits of soil clinging to the bottom of the stalk or leaves (Figure 1.23). Rub the soil between your thumb and fingers. Smooth, very black soil may indicate that the lettuce was grown in mucky soils, such as those in New York State or southern Florida. Light brown, smooth-feeling soil with only a very fine grittiness is more typical of California-grown produce, whereas light-colored, gritty soil is common on produce from the sandy coastal soils (such as southern Georgia–northern Florida vegetable-growing region). In a bag of dry beans, you may come across a few lumps of soil that escaped removal in the cleaning process because of being the same size as the beans. Often this soil is dark-colored and very sticky, coming from the "thumb" area of Michigan, where a large portion of the U.S. dry bean crop is grown on clayey lake-bed soils.

Opportunities to observe soils in daily life range from the remote and large-scale to the close-up and intimate. As you learn more about soils, you will undoubtedly be able to see more examples of their influence in your surroundings.

Figure 1.22 *The light- and dark-colored soil bodies, as seen from an airliner flying over central Texas, reflect differences in drainage, erosion, and topography in the landscape.* (Photo courtesy of Ray R. Weil)

Figure 1.23 *Although this celery was purchased in a Virginia grocery store in early fall, the black, mucky soil clinging to the base of the stalk indicates that it was grown on organic soils, probably in New York State, USA.* (Photo courtesy of Ray R. Weil)

Soil Minerals

Minerals that have persisted with little change in composition since they were extruded in molten lava (e.g., quartz, micas, and feldspars) are known as **primary minerals**. They are prominent in the sand and silt fractions of soils and contain many of the nutrient elements needed by plants. Other minerals, such as silicate clays and iron oxides, were formed by the breakdown and weathering of less resistant minerals as soil formation progressed. These minerals are called **secondary minerals** and tend to dominate the clay and, in some cases, silt fractions. Soil mineralogical signatures are one of the clues used by forensic soil scientists to locate crime victims or establish guilt by matching soil clinging to shoes, tires, tools, or under fingernails with soil from a crime scene (Figure 1.24).

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Figure 1.24 *Soil can be useful in solving crime mysteries and is often placed in evidence in court proceedings. The mud clinging to these boots* (center) *was used to prove the innocence of a man accused of robbery and breaking into a house. In this case the type of sand grains found in the mud from the boots was typical of quartz-rich soils* (left)*, which occurred at the job site of the accused but not anywhere near the crime site, which instead had soils with mica-rich sands* (right)*. The largest sand grains in both photos are about 1 mm in diameter.*
(Photos courtesy of Ray R. Weil)

Soil Structure

Sand, silt, and clay particles can be thought of as the building blocks from which soil is constructed. **Soil structure** describes the way these building blocks are associated together in aggregates of various sizes and shapes (see, e.g., the nature of the soil "clumps" in Figure 1.18, *right*). Soil structure (the way particles are arranged together) is just as important as soil texture (the relative amounts of different sizes of particles) in governing how water and air move in soils. Both structure and texture fundamentally influence many processes in soil, including the growth of plant roots.

1.14 THE NATURE OF SOIL ORGANIC MATTER

Soil organic matter consists of a wide range of organic (carbonaceous) substances, including living organisms (the soil ***biomass***), carbonaceous remains of organisms that once occupied the soil, and organic compounds produced by current and past metabolism in the soil. Over time, organic matter is destroyed by microbial respiration and its carbon is lost from the soil as carbon dioxide. Because of such losses, repeated additions of new plant and/or animal residues are necessary to maintain soil organic matter.

Under conditions that favor plant production more than microbial decay, large quantities of atmospheric carbon dioxide used by plants in photosynthesis are sequestered in the abundant plant tissues that eventually become part of the soil organic matter. Since carbon dioxide is a major greenhouse gas whose increase in the atmosphere is warming Earth's climate, the balance between accumulation of soil organic matter and its loss through microbial respiration has global implications. In fact, more carbon is stored in the world's soils than in the world's plant biomass and atmosphere combined.

Even so, organic matter comprises only a small fraction of the mass of a typical soil. By weight, typical well-drained mineral surface soils contain from 1 to 6% organic matter. The organic matter content of subsoils is even smaller. However, the influence of organic matter on soil properties, and consequently on plant growth, is far greater than the low percentage would indicate (see also Chapter 12).

Organic matter binds mineral particles into a granular soil structure that is largely responsible for the loose, easily managed condition of productive soils. Part of the soil organic matter that is especially effective in stabilizing these granules consists of certain glue-like substances produced by various soil organisms, including plant roots (Figure 1.25).

Organic matter also increases the amount of water a soil can hold and the proportion of water available for plant growth (Figure 1.26). In addition, organic matter is a major source of the plant nutrients nitrogen, phosphorus, and sulfur. As soil organic matter decays, these nutrient elements, which are present in organic combinations, are released as soluble ions that

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Figure 1.25 *Abundant organic matter, including plant roots, helps create physical conditions favorable for the growth of higher plants as well as microbes* (left). *In contrast, soils low in organic matter, especially if they are high in silt and clay, are often cloddy* (right) *and not suitable for optimum plant growth.* (Photo courtesy of Ray R. Weil)

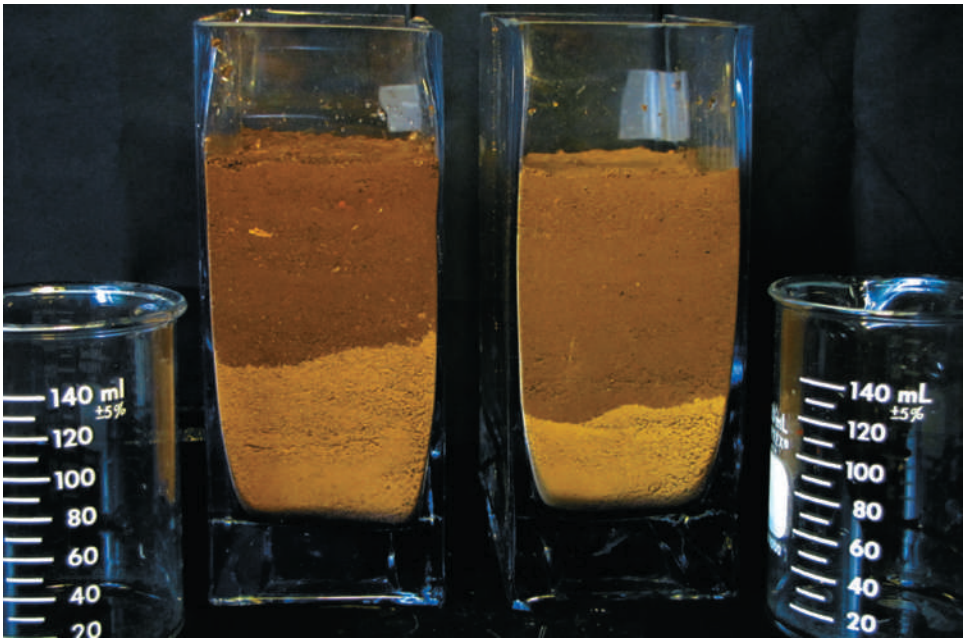

Figure 1.26 *Soils higher in organic matter are darker in color and have greater water-holding capacities than soils low in organic matter. The soil in each container has the same texture, but the one on the right has been depleted of much of its organic matter. The same amount of water was applied to each container. As the photo shows, the depth of water penetration was less in the high organic matter soil* (left) *because of its greater water-holding capacity. It required a greater volume of the low organic matter soil to hold the same amount of water.* (Photo courtesy of Ray R. Weil)

can be taken up by plant roots. Finally, organic matter, including plant and animal residues, is the main food that supplies carbon and energy to soil organisms. Without it, biochemical activity so essential for ecosystem functioning would come to a near standstill.

Humus, usually black or brown in color, is a collection of organic compounds that accumulate in soil when partially broken down plant and animal residues are protected from complete decay by various factors in the soil environment. Like clay, much of the soil's humus is colloidal in size and exhibits highly charged surfaces. Both humus and clay act as contact bridges between larger soil particles; thus, both play an important role in the formation of soil structure. The surface charges of humus, like those of clay, attract and hold both nutrient ions and water molecules. However, gram for gram, the capacity of humus to hold nutrients and water is far greater than that of clay. Unlike clay, humus may contain components that can make micronutrients more easily used by plants and may even cause hormone-like stimulation of certain plant processes. All in all, small amounts of humus remarkably increase the soil's capacity to promote plant growth.

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1.15 SOIL WATER—DYNAMIC AND COMPLEX

The soil moisture regime, often reflective of climatic factors, is a major determinant of the productivity of terrestrial ecosystems, including agricultural systems. Movement of water, and substances dissolved in it, through the soil profile impacts both the quality and quantity of local and regional water resources. Water moving through the regolith is also a major driving force in soil formation (see Box 2.1).

Two main factors help explain why **soil water** is different from our everyday concept of, say, drinking water in a glass:

1. Water is held within soil pores where the attraction between water and the surfaces of soil particles greatly restricts the ability of water to flow as it would flow in a drinking glass.
2. Because soil water is never pure water, but contains hundreds of dissolved organic and inorganic substances, it may be more accurately called the ***soil solution***. An important function of the soil solution is to serve as a constantly replenished, dilute nutrient solution bringing dissolved nutrient elements (e.g., calcium, potassium, nitrogen, and phosphorus) to plant roots.

When the soil moisture content is optimal for plant growth (Figure 1.21), the water in the large- and intermediate-sized pores can move about in the soil and can easily be used by plants. The plant roots, however, remove water from the largest pores first. Soon the larger pores hold only air, and the remaining water is found only in the intermediate- and smallest-sized pores. The water in the intermediate-sized pores can still move toward plant roots and be taken up by them. However, the water in the smallest pores is so close to solid particles that it may be so strongly held that plant roots cannot pull it away. Consequently, not all soil water is *available* to plants. Depending on the soil, one-sixth to one-half of the water may remain in the soil after plants have wilted or died for lack of moisture.

Soil Solution

The soil solution contains small but significant quantities of soluble organic and inorganic substances, including the plant nutrients listed in Table 1.1. The soil solids, particularly the fine organic and inorganic colloidal particles (clay and humus), release nutrient elements to the soil solution from which they are taken up by plant roots. The soil solution tends to resist changes in its composition even when compounds are added or removed from the soil. This ability to resist change is termed the soil **buffering capacity** and is dependent on many chemical and biological reactions, including the attraction and release of substances by colloidal particles (see Chapter 8).

Many chemical and biological reactions are controlled by the relative amounts of acidity caused by a dominance of hydrogen ions (H^+) and alkalinity caused by a dominance of hydroxyl ions (OH^-) in the soil solution (Figure 1.27). The **pH** is a logarithmic scale used to express the degree of soil acidity or alkalinity (see Chapter 9, especially Box 9.1 and Figure 9.2). The pH is

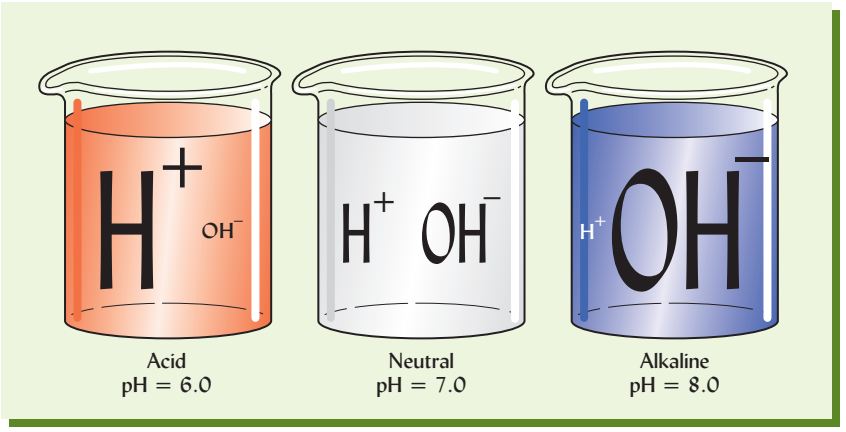

Figure 1.27 *Diagram representing acidity, neutrality, and alkalinity. At neutrality (pH = 7), H^+ and OH^- ions are present in equal numbers. At pH 6, there are 10 times more H^+ ions than at pH 7, while the number of OH^- ions is 10 times less than at pH7. Thus at pH 6 H^+ outnumber OH^- ions 100 to 1 and the solution is therefore acid. Conversely, at pH 8 the OH^- are 100 times more plentiful than the H^+ and the solution is alkaline. This mutually inverse relationship between H^+ and OH^- ions must be kept in mind whenever pH data are considered.* (Diagram courtesy of N. C. Brady)

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considered a master variable that influences most chemical processes in the soil and is of great significance to nearly all aspects of soil science.

1.16 SOIL AIR: A CHANGING MIXTURE OF GASES

Think how stuffy the air would become if the ventilation ducts of a windowless classroom became clogged. If we think of the network of soil pores as the ventilation system of the soil connecting airspaces to the atmosphere, we can understand that when pores are filled with water the ventilation system becomes clogged. Because oxygen could neither enter the room nor carbon dioxide leave it, the air in the room would soon become depleted of oxygen and enriched in carbon dioxide and water vapor by the respiration (breathing) of the people in it. In an air-filled soil pore surrounded by water-filled smaller pores, the metabolic activities of plant roots and microorganisms have a similar effect.

Therefore, soil air differs from atmospheric air in several respects. First, the composition of soil air varies greatly from place to place in the soil. In local pockets, some gases are consumed by plant roots and by microbial reactions, and others are released, thereby greatly modifying the composition of the soil air. Second, soil air generally has a higher moisture content than the atmosphere; the relative humidity of soil air approaches 100% unless the soil is very dry. Third, the content of carbon dioxide (CO_2) is usually much higher, and that of oxygen (O_2) lower, than contents of these gases found in the atmosphere. Carbon dioxide in soil air is often several hundred times more concentrated than the 0.035% commonly found in the atmosphere. Oxygen decreases accordingly and, in extreme cases, may be 5–10%, or even less, compared to about 20% for atmospheric air. In extreme cases, lack of oxygen both in the soil air and dissolved in the soil water may fundamentally alter the chemical reactions that take place in the soil solution. This is of particular importance to understanding the functions of wetland soils.

The amount and composition of air in a soil are determined to a large degree by the water content of the soil. When water enters the soil, it displaces air from some of the pores; the air content of a soil is therefore inversely related to its water content. As the soil drains from a heavy rain or irrigation, large pores are the first to be filled with air, followed by medium-sized pores, and finally the small pores, as water is removed by evaporation and plant use. This explains the tendency for soils with a high proportion of tiny pores to be poorly aerated.

1.17 HOW DO SOIL COMPONENTS INTERACT TO SUPPLY NUTRIENTS TO PLANTS?

As you read our discussion of each of the four major soil components, you may have noticed that the impact of one component on soil properties is seldom expressed independently from that of the others. Rather, the four components interact with each other to determine the nature of a soil. Thus, soil moisture, which directly meets the needs of plants for water, simultaneously controls much of the air and nutrient supply to the plant roots. The mineral particles, especially the finest ones, attract soil water, thus determining its movement and availability to plants. Likewise, organic matter, because of its physical binding power, influences the arrangement of the mineral particles into clusters and, in so doing, increases the number of large soil pores, thereby influencing the water and air relationships.

Essential Element Availability

Perhaps the most important interactive process involving the four soil components is the provision of essential nutrient elements to plants. Plants absorb essential nutrients, along with water, directly from one of these components: the soil solution. However, the amount of essential nutrients in the soil solution at any one time is sufficient to supply the needs of growing vegetation for only a few hours or days. Consequently, the soil solution nutrient levels must be constantly replenished from the inorganic or organic parts of the soil and from fertilizers or manures added to agricultural soils.

By a series of chemical and biochemical processes, nutrients are released from these solid forms to replenish those in the soil solution. For example, the tiniest colloidal-sized particles—both clay and humus—exhibit negative and positive charges. These charges tend to

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Table 1.3
QUANTITIES OF SIX ESSENTIAL ELEMENTS FOUND IN UPPER 15 CM OF REPRESENTATIVE SOILS IN TEMPERATE REGIONS

	Humid Region Soil			Arid Region Soil		
Essential element	In solid framework, kg/ha	Exchangeable, kg/ha	In soil solution, kg/ha	In solid framework, kg/ha	Exchangeable, kg/ha	In soil solution, kg/ha
Ca	8,000	2,250	60–120	20,000	5,625	140–280
Mg	6,000	450	10–20	14,000	900	25–40
K	38,000	190	10–30	45,000	250	15–40
P	900	—	0.05–0.15	1,600	—	0.1–0.2
S	700	—	2–10	1,800	—	6–30
N	3,500	—	7–25	2,500	—	5–20

attract or **adsorb**[6] oppositely charged ions from the soil solution and hold them as **exchangeable ions**. Through ion exchange, elements such as Ca^{2+} and K^{+} are released from this state of electrostatic adsorption on colloidal surfaces and escape into the soil solution where they can be readily taken up (absorbed) by plant roots. Some scientists consider that this ion exchange process is among the most important of chemical reactions in nature.

Nutrient ions are also released to the soil solution as soil microorganisms decompose organic tissues. Plant roots can readily absorb all of these nutrients from the soil solution, provided there is enough O_2 in the soil air to support root metabolism.

Most soils contain large amounts of plant nutrients relative to the annual needs of growing vegetation. However, the bulk of most nutrient elements is held in the structural framework of primary and secondary minerals and organic matter. Only a small fraction of the nutrient content of a soil is present in forms that are readily available to plants. Table 1.3 will give you some idea of the quantities of various essential elements present in different forms in typical soils of humid and arid regions.

Figure 1.28 illustrates how the two solid soil components interact with the liquid component (soil solution) to provide essential elements to plants. Plant roots do not ingest soil particles, no matter how fine, but are able to absorb only nutrients that are dissolved in the soil solution. Because elements in the coarser soil framework of the soil are only slowly released into the soil solution over long periods of time, the bulk of most nutrients in a soil is not readily available for plant use. Nutrient elements in the framework of colloid particles are somewhat more readily available to plants, as these particles break down much faster because of their greater surface area. Thus, the structural framework is the major storehouse and, to some extent, a significant source of essential elements in many soils.

The distribution of nutrients among the various components of a fertile soil, as illustrated in Figure 1.28, may be likened to the distribution of financial assets in the portfolio of a wealthy individual. Nutrients readily available for plant use would be analogous to cash in the individual's pocket. A millionaire would likely keep most of his or her assets in long-term investments such as real estate or bonds (the coarse fraction solid framework), while investing a smaller amount in short-term stocks and bonds (colloidal framework). For more immediate use, an even smaller amount might be kept in a checking account linked to an automated teller machine (exchangeable nutrients), while a tiny fraction of the overall wealth might be carried to spend as currency and coins (nutrients in the soil solution). As the cash is used up, the supply is replenished by making a withdrawal from the ATM. The checking account, in turn, is replenished occasionally by the sale of long-term investments. It is possible for wealthy persons to run short of coins for a vending

[6]*Adsorption* refers to the attraction of ions to the surface of particles, in contrast to *absorption*, the process by which ions are taken *into* plant roots. The adsorbed ions are exchangeable with ions in the soil solution.

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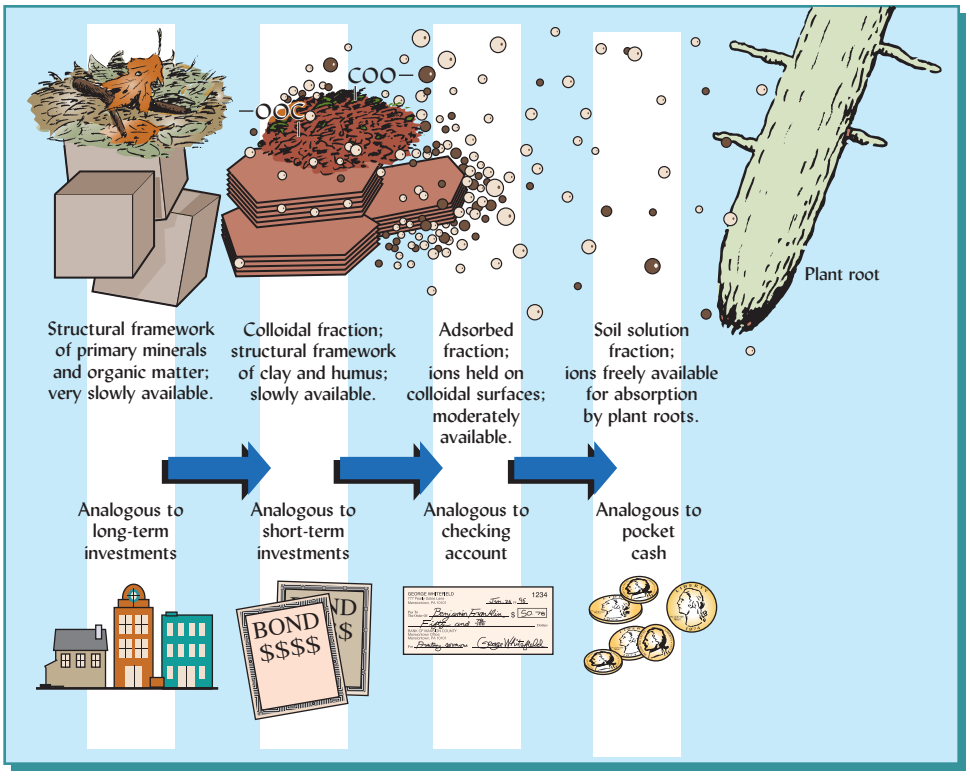

Figure 1.28 *Nutrient elements exist in soils in various forms characterized by different accessibility to plant roots. The bulk of the nutrients is locked up in the structural framework of primary minerals, organic matter, clay, and humus. A smaller proportion of each nutrient is adsorbed in a swarm of ions near the surfaces of soil colloids (clay and organic matter). From the swarm of adsorbed ions, a still smaller amount is released into the bulk soil solution, where uptake by plant roots can take place. The lower diagram considers the analogy between financial assets and nutrient assets.* (Diagram courtesy of Ray R. Weil)

machine even though they may own a great deal of valuable real estate. In an analogous way, plants may use up the readily available supply of a nutrient even though the total supply of that nutrient in the soil is very large. Luckily, in a fertile soil, the process described in Figure 1.28 can help replenish the soil solution as quickly as plant roots remove essential elements.

1.18 HOW DO PLANT ROOTS OBTAIN NUTRIENTS?

To be taken up by a plant, the nutrient element must be in a soluble form and must be located *at the root surface*. Often, parts of a root are in such intimate contact with soil particles (see Figure 1.29) that a direct exchange may take place between nutrient ions adsorbed on the surface of soil colloids and H^+ ions from the surface of root cell walls. In any case, the supply of nutrients in contact with the root will soon be depleted. So how can a root obtain additional supplies once the nutrient ions at the root surface have all been taken up into the root? There are three basic mechanisms by which the concentration of nutrient ions at the root surface is maintained (Figure 1.30).

First, **root interception** comes into play as roots continually grow into new, undepleted soil. Root exploration in search of nutrients is much enhanced by thin root cell extensions called **root hairs**. In fact, root hair growth was recently discovered to be controlled by a regulatory plant gene that is "turned on" by low nutrient conditions. Even with root hairs extending into tiny water-filled soil pores where nutrients may be dissolved, for the most part, nutrient ions must still travel some distance in the soil solution to reach the root surface. This movement can take place by **mass flow**, as when dissolved nutrients are carried along with the flowing soil water toward a root that is actively drawing water from the soil. In this type of movement, the nutrient ions are somewhat analogous to leaves floating down a stream. On the other hand, plants can continue to take up nutrients even at night, when little, if any, water is absorbed into the roots. Nutrient ions continually move by **diffusion** from areas of greater concentration toward the nutrient-depleted areas of lower concentration around the root surface.

In the diffusion process, the random movements of ions in all directions causes a *net* movement from areas of high concentration to areas of lower concentrations, independent of any mass flow of the water in which the ions are dissolved. Factors such as soil compaction, cold temperatures, and low soil moisture content, which reduce root interception, mass flow, or diffusion, can result in poor nutrient uptake by plants even in soils with adequate supplies

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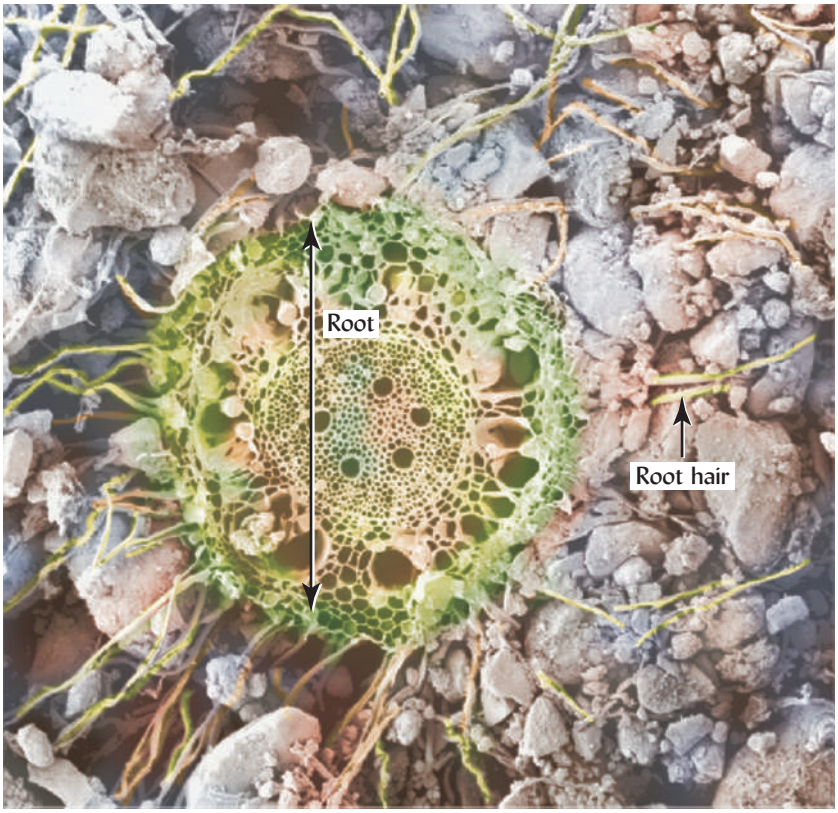

Figure 1.29 *Cross section of a barley root growing in field soil. Note the intimate contact between the root and the soil, made more so by the long, thin root hairs that permeate the nearby soil and bind it to the root. The root itself is about 0.3 mm in diameter.* (Cryo scanning electron micrograph courtesy of Margaret McCully, CSIRO, Plant Industry, Canberra, Australia)

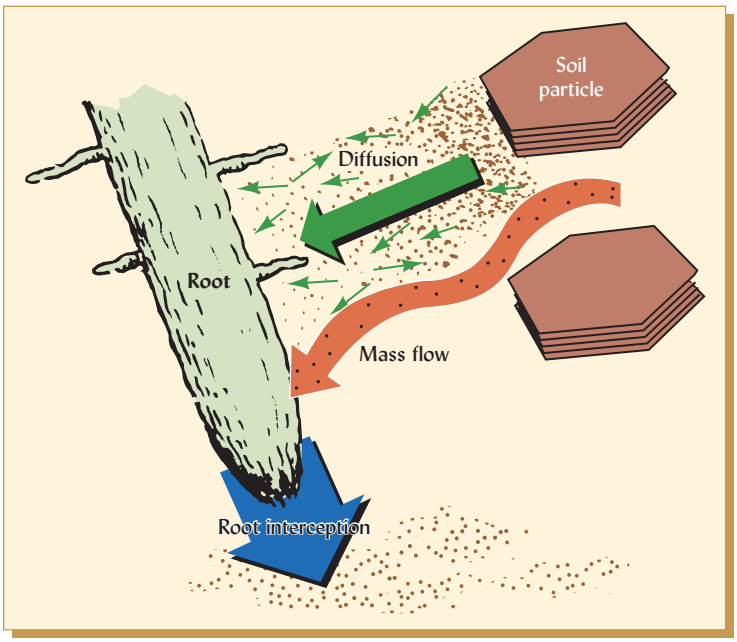

Figure 1.30 *Three principal mechanisms by which nutrient ions dissolved in the soil solution come into contact with plant roots. All three mechanisms may operate simultaneously, but one mechanism or another may be most important for a particular nutrient. For example, in the case of calcium, which is generally plentiful in the soil solution, mass flow alone can usually bring sufficient amounts to the root surface. However, in the case of phosphorus, diffusion is needed to supplement mass flow because the soil solution is very low in this element in comparison to the amounts needed by plants.* (Diagram courtesy of Ray R. Weil)

of soluble nutrients. Furthermore, the availability of nutrients for uptake can also be negatively or positively influenced by the activities of microorganisms that thrive in the immediate vicinity of roots. Maintaining the supply of available nutrients at the plant root surface is thus a process that involves complex interactions among different soil components.

It should be noted that the plant membrane separating the inside of the root cell from the soil solution is permeable to dissolved ions only under special circumstances. Plants do not merely take up, by mass flow, those nutrients that happen to be in the water that roots are removing from the soil. Nor do dissolved nutrient ions brought to the root's outer surface by mass flow or diffusion cross the root cell membrane and enter the root passively by diffusion.

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On the contrary, a nutrient is normally taken up into the plant root cell only by reacting with specific chemical binding sites on large protein molecules embedded in the root membrane. These proteins form hydrophilic channels across an otherwise hydrophobic lipid (fatty) membrane. Energy from metabolism in the root cell is used to activate this carrier protein so that it will pass the nutrient ion across the cell membrane and release it into the cell interior. This carrier mechanism allows the plant to accumulate concentrations of a nutrient inside the root cell that far exceed that nutrient's concentration in the soil solution. Because different nutrients are taken up by specific types of protein molecules, the plant is able to exert some control over how much and in what relative proportions essential elements are taken up.

Nutrient uptake being an active metabolic process, conditions that inhibit root metabolism may also inhibit nutrient uptake. Examples of such conditions include excessive soil water content or soil compaction resulting in poor soil aeration, excessively hot or cold soil temperatures, and aboveground conditions that result in low translocation of sugars to plant roots. We can see that plant nutrition involves biological, physical, and chemical processes and interactions among many different components of soils and the environment.

1.19 SOIL HEALTH, DEGRADATION, AND RESILIENCE

Soil is a basic resource underpinning all terrestrial ecosystems. Managed carefully, soils are a *reusable* resource, but in the scale of human lifetimes they cannot be considered a *renewable* resource. As we shall see in the next chapter, most soil profiles are thousands of years in the making. In all regions of the world, human activities are destroying some soils far faster than nature can rebuild them. Growing numbers of people are demanding more and more ecosystem services from the Earth's fixed amount of land. This situation presents soil scientists and humanity with a number of grand challenges that must be met if human civilization and nature are to be sustained side by side (Table 1.4).

In most parts of the world, nearly all of the soils best suited for growing crops are already being farmed. Therefore, as each year brings millions more people to feed, the amount of cropland per person continuously declines. In addition, many of the world's major cities were originally located where excellent soils supported thriving agricultural communities. Without policies to protect farmland, many of the very best soils for farming are lost to suburban development as these cities expand.

Finding more land on which to grow food is not easy. Most additional land brought under cultivation comes at the cost of clearing natural forests, savannas, and grasslands. Images of the Earth made from orbiting satellites show the resulting decline in land covered by forests and other natural ecosystems. Thus, as the human population struggles to feed itself, wildlife populations are deprived of vital habitat, and overall biodiversity suffers. Efforts to reduce and even reverse human population growth must be accelerated if our grandchildren are to inherit a livable world. In the meantime, if there is to be space for both people and wildlife, the best of our existing farmland soils will require improved and more intensive management. While soils completely washed away by erosion or excavated and paved over by urban sprawl are permanently lost, many more soils are degraded in quality rather than totally destroyed.

Soil Quality and Health

People who work with the land and depend on soils to perform critical functions want to improve and maintain **soil health**. They recognize that soils are living systems with highly complex and diverse communities of organisms. In their optimal state, these organisms work together to function in a self-regulating and perpetuating manner (Chapter 20). Healthy soils function more efficiently with less need for expensive human interventions and inputs than unhealthy, degraded soils. **Soil quality** is a measure of the ability of a soil to carry out particular ecological functions, such as those described in Sections 1.2–1.7. Soil quality reflects a combination of *chemical*, *physical*, and *biological* properties. Some of these properties are relatively unchangeable, inherent properties that help define a particular type of soil. Soil texture and mineral makeup (Section 1.13) are examples. Other soil properties, such as structure (Section 1.13) and organic matter content (Section 1.14), can be significantly changed by management. These more changeable soil properties can indicate the status of a soil's quality relative

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Table 1.4
GRAND SOIL SCIENCE CHALLENGES FOR 2050

No.	Topic Area	Grand Challenge
1	Food	How can we feed 2 billion *more* people than today without harming our soils or the broader environment?
2	Nutrients	How do we preserve and enhance the fertility of our soils, conserve scarce nutrient resources and also export nutrients from farms to cities in ever bigger harvests?
3	Fresh water	How can we manage our soils to use dwindling water supplies more efficiently and wisely while managing soils to protect our waters from pollution?
4	Energy	How can we sustainably manage our lands to contribute to energy supplies by integrating biochar use and producing biofuel feedstocks?
5	Climate change	How can we manage soils to mitigate climate change by reducing greenhouse gases while also adapting to climate change by protecting soil productivity and resilience?
6	Biodiversity	How can we better understand and enhance the biotic communities within and on the soil to create more resilient and productive ecosystems and utilize the diverse gene pool?
7	Recycling "wastes"	How can we better use soils as biogeochemical reactors to avoid contamination, detoxify contaminants, and maintain soil productivity?
8	Global perspective	How can we develop a global perspective that still permits us to optimize management of local places, wherever they may be?

Modified from Janzen et al. (2011)

to its potential, in much the same way that water turbidity or oxygen content indicates the water-quality status of a river.

Soil Degradation and Resilience

Mismanagement of forests, farms, and rangeland causes widespread degradation of soil quality by erosion that removes the topsoil, little by little (see Chapter 17). Another widespread cause of soil degradation is the accumulation of salts in improperly irrigated soils in arid regions (see Chapter 10). When people cultivate soils and harvest the crops without returning organic residues and mineral nutrients, the soil's supply of organic matter and nutrients becomes depleted (see Chapter 12). Such depletion is particularly widespread in sub-Saharan Africa, where degrading soil quality is reflected in diminished capacity to produce food (see Chapter 20). Contamination of a soil with toxic substances from industrial processes or chemical spills can degrade its capacity to provide habitat for soil organisms, to grow plants that are safe to eat, or to safely recharge ground and surface waters (see Chapter 18). Degradation of soil quality by pollution is usually localized, but the environmental impacts and costs involved are very large.

While protecting soil quality must be the first priority, it is often necessary to attempt to restore the quality of soils that have already been degraded. Some soils have sufficient **resilience** to recover from minor degradation if left to regenerate on their own. In other cases, more effort is required to restore degraded soils (see Chapter 17). Organic and inorganic amendments may have to be applied, vegetation may have to be planted, physical alterations by tillage or grading may have to be made, or contaminants may have to be removed. As societies around the world assess the damage already done to their natural and agricultural ecosystems, the science of **restoration ecology** has rapidly evolved to guide managers in restoring plant and animal communities to their former levels of diversity and productivity. The job of **soil restoration**, an essential part of these efforts, requires in-depth knowledge of all aspects of the soil system.

1.20 CONCLUSION

The Earth's soil is comprised of numerous soil individuals, each of which is a three-dimensional natural body in the landscape. Each individual soil is characterized by a unique set of properties and soil horizons as expressed in its profile. The nature of the soil layers seen in a particular profile is closely related to the nature of the environmental conditions at a site.

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Soils perform six broad ecological functions: they act as the principal medium for plant growth, regulate water supplies, modify the atmosphere, recycle raw materials and waste products, provide habitat for many kinds of organisms, and serve as a major engineering medium for human-built structures. Soil is thus a major ecosystem in its own right. The soils of the world are extremely diverse, each type of soil being characterized by a unique set of soil horizons. A typical surface soil in good condition for plant growth consists of about half solid material (mostly mineral, but with a crucial organic component, too) and half pore spaces filled with varying proportions of water and air. These components interact to influence a myriad of complex soil functions, a good understanding of which is essential for wise management of our terrestrial resources.

If we take the time to learn the language of the land, the soil will speak to us.

STUDY QUESTIONS

1. As a society, is our reliance on soils likely to increase or decrease in the decades ahead? Explain.
2. Discuss how *a soil*, a natural body, differs from *soil*, a material that is used in building a roadbed.
3. What are the six main roles of soil in an ecosystem? For each of these ecological roles, suggest one way in which interactions occur with another of the six roles.
4. Think back over your activities during the past week. List as many incidents as you can in which you came into direct or indirect contact with soil.
5. Figure 1.21 shows the volume composition of a loam surface soil in ideal condition for plant growth. To help you understand the relationships among the four components, redraw this pie chart to represent what the situation might be after the soil has been compacted by heavy traffic. Then draw another pie chart to show how the four components of the original ideal soil would be related on a mass (weight) basis rather than on a volume basis.
6. Explain in your own words how the soil's nutrient supply is held in different forms, much the way that a person's financial assets might be held in different forms.
7. List the essential nutrient elements that plants derive mainly from the soil.
8. Are all elements contained in plants essential nutrients? Explain.
9. Define these terms: *soil texture*, *soil structure*, *soil pH*, *humus*, *soil profile*, *B horizon*, *soil quality*, *solum*, and *saprolite*.
10. Describe four processes that commonly lead to degradation of soil quality.
11. Compare the pedological and edaphological approaches to the study of soils. Which is more closely aligned with geology and which with ecology?
12. Which of the *grand challenges* listed in Table 1.4 is most exciting and inspiring to you, and why?

REFERENCES

Abrahams, P. W. 2005. "Geophagy and the involuntary ingestion of soil," pp. 435–457, in O. Selinus (ed.), *Essentials of Medical Geology*. Elsevier, The Hauge.

Abrahams, P. W. 2012. "Involuntary soil ingestion and geophagia: A source and sink of mineral nutrients and potentially harmful elements to consumers of earth materials," *Appl Geochem.*, **27**:in press.

Alloway, B. J., and R. D. Graham. 2008. "Micronutrient deficiencies in crops and their global significance," pp. 41–61, in B. J. Alloway (ed.), *Micronutrient Deficiencies in Global Crop Production*. Springer, Netherlands.

Epstein, E., and A. J. Bloom. 2005. *Mineral Nutrition of Plants: Principles and Perspectives*. 2nd ed. Sinauer Associates, Sunderland, MA. 400 p.

Fisher, M. 2012. "Investigating the earth's critical zone," *CSA News*, **57**(1):5–9.

Frager, S. Z., C. J. Chrisman, R. Shakked, and A. Casadevall. 2010. "Paramecium species ingest and kill the cells of the human pathogenic fungus cryptococcus neoformans," *Med Mycol.*, **48**:775–779.

Griffin, D. W. 2007. "Atmospheric movement of microorganisms in clouds of desert dust and implications for human health," *Clin Microbiol Rev.*, **20**:459–477.

Janzen, H. H., P. E. Fixen, A. J. Franzluebbers, J. Hattey, R. C. Izaurralde, Q. M. Ketterings, D. A. Lobb, and W. H. Schlesinger. 2011. "Global prospects rooted in soil science," *Soil Sci Soc Am J.*, **75**:1–8.

Liu, T., and C. Khosla. 2010. "A balancing act for taxol precursor pathways in e. Coli," *Science*, **330**:44–45.

Otto, C. C., and S. E. Haydel. 2013. "Exchangeable ions are responsible for the *in vitro* antibacterial properties of natural clay mixtures," *PLoS ONE*, **8**:e64068.

Rook, G. A. 2013. "Regulation of the immune system by biodiversity from the natural environment: An ecosystem service essential to health," *Proc Natl Acad Sci.*, **110**:18360–18367.

Stokes, T. 2006. "The earth-eaters," *Nature*, **444**:543–544.

Young, S. L., P. W. Sherman, J. B. Lucks, and G. H. Pelto. 2011. "Why on earth?: Evaluating hypotheses about the physiological functions of human geophagy," *Q Rev Bio.*, **86**:97–120.

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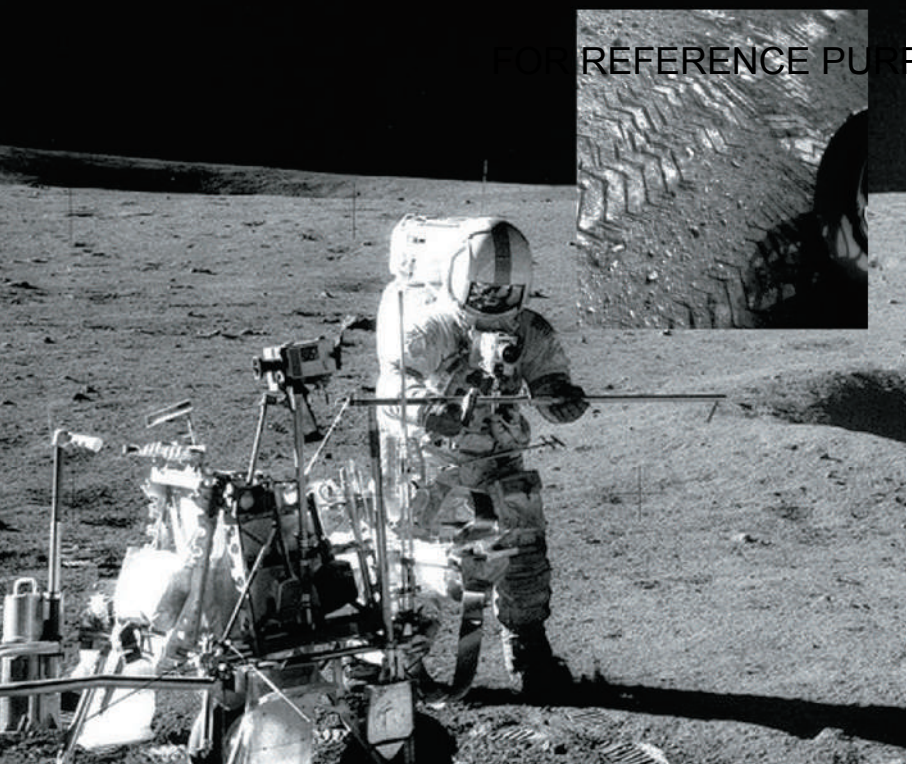

Leaving tracks in the soils of other worlds: Apollo 14 astronaut sampling lunar soil with inset showing tracks of Curiosity Rover in Mars soil. (NASA)

2 Formation of Soils from Parent Materials

It is a poem of existence . . . not a lyric but a slow epic whose beat has been set by eons of the world's experience. . . .
—*James Michener,* Centennial

The first astronauts to explore the moon labored in their clumsy pressurized suits to collect samples of rocks and dust from the lunar surface. These they carried back to Earth for analysis. It turned out that moon rocks are similar in composition to those found deep in the Earth—so similar that scientists concluded that the moon itself began when a stupendous collision between a Mars-sized object named Theia and the young Earth spewed molten material into orbit around the planet.[1] The force of gravity eventually pulled this material together to form the moon. On the moon, this rock remained unchanged or crumbled into dust with the impact of meteors. On Earth, the rock at the surface, eventually coming in contact with water, air, and living things, was transformed into something new, into many different kinds of living soils. This chapter reveals the story of how rock and dust become "the ecstatic skin of the Earth."[2]

We will study the processes of soil formation that transform the lifeless regolith into the variegated layers of the soil profile. We will also learn about the environmental factors that influence these processes to produce soils in Belgium so different from those in Brazil, soils on limestone so different from those on sandstone, and soils in the valley bottoms so different from those on the hills.

Every landscape is comprised of a suite of different soils, each influencing ecological processes in its own way. Whether we intend to modify, exploit, preserve, or simply understand the landscape, our success will depend on our knowing how soil properties relate to the environment on each site and to the landscape as a whole.

2.1 WEATHERING OF ROCKS AND MINERALS

Weathering breaks up rocks and minerals, modifies or destroys their physical and chemical characteristics, and carries away the finer fragments and soluble products. Nothing escapes it. However, weathering also synthesizes new minerals that influence important properties

[1]Computer simulations suggest that formation of the moon from such a collision would have resulted in the moon rock made of about 80% Theia material and 20% Earth material. Isotopic analysis of basalt rock samples some 40 years after their collection on the moon by the Apollo astronauts supports this scenario (Herwartz et al., 2014).
[2]The apt description of soil as "ecstatic skin of the Earth" is from a delightfully readable account of soils by Logan (1995). However, Earth may not be the only planet with a skin of soil. Intriguing data from Mars Rover landers and the OMEGA orbiter suggest erosion and formation of secondary minerals like gypsum from the movement and evaporation of surface water but almost no weathering and no clays. Although scientists have concluded that the Martian surface has been dry and cold since brief flooding 600 million years ago, some intriguing observation suggests still active warm season flows (Ojha, et al., 2015 and McEwen et al., 2011).

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Figure 2.1 *Two stone markers, photographed on the same day in the same cemetery, illustrate the effect of rock type on weathering rates. The date and initials carved in the slate marker in 1798 are still sharp and clear, while the date and figure of a lamb carved in the marble marker in 1875 have weathered almost beyond recognition. The slate rock consists largely of resistant silicate clay minerals, whereas the marble consists mainly of calcite, which is much more easily attacked by acids in rainwater.* (Photos courtesy of Ray R. Weil)

in soils. The nature of the rocks and minerals being weathered determines the rates and results of the breakdown and synthesis (Figure 2.1).

Characteristics of Rocks and Minerals

Geologists classify Earth's rocks as igneous, sedimentary, and metamorphic. Igneous rocks are those formed from molten magma and include such common rocks as granite and diorite (Figure 2.2).

Igneous rock is composed of such primary minerals[3] as light-colored quartz, muscovite, and feldspars and dark-colored biotite, augite, and hornblende. The mineral grains in igneous rocks interlock and are randomly dispersed, giving a salt-and-pepper appearance if they are coarse enough to see with the unaided eye (Figure 2.3). In general, dark-colored minerals contain iron and magnesium and are more easily weathered. Therefore, dark-colored igneous rocks such as gabbro and basalt are more easily broken down than are granite, syenite, and other lighter-colored igneous rocks.

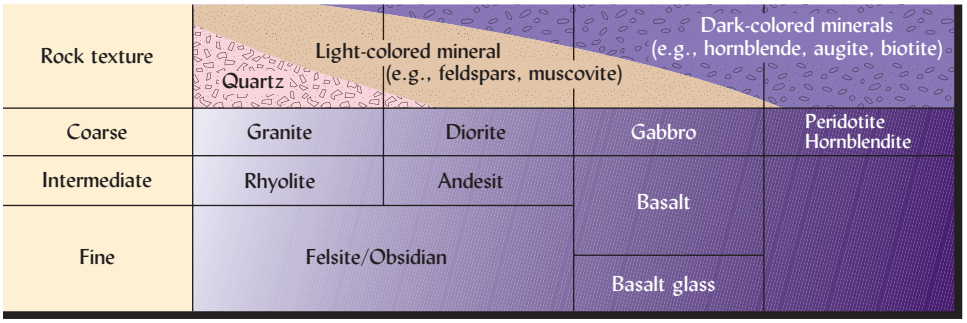

Figure 2.2 *Classification of some igneous rocks in relation to mineralogical composition and the size of mineral grains in the rock (rock texture). Worldwide, light-colored minerals and quartz are generally more prominent than the dark-colored minerals.*

[3]*Primary minerals* have not been altered chemically since they formed as molten lava solidified. *Secondary minerals* are recrystallized products of the chemical breakdown and/or alteration of primary minerals.

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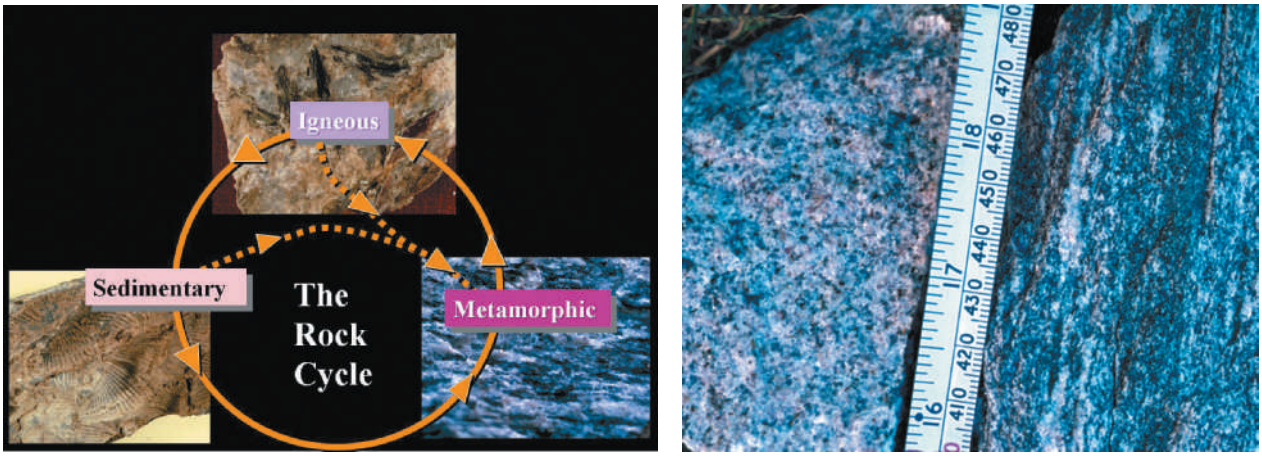

Figure 2.3 (Left) *The three rock types are interrelated by processes that comprise the rock cycle.* (Right) *Primary minerals are randomly interlocked in igneous rocks, as in the syenite to the left of the scale. High heat and pressure have deformed and reoriented the crystals and caused lighter minerals to separate from heavier ones, forming the light- and dark-colored bands typical of gneiss, a metamorphic rock on the right of the scale. In this case, the primary mineral content of both rocks is similar, the light-colored minerals being mainly feldspars and the darker ones hornblende. Scale in inches and centimeters.* (Photo courtesy of Ray R. Weil)

Sedimentary rocks form when weathering products released from other, older rocks collect under water as sediment and eventually reconsolidate into new rock. For example, quartz sand weathered from granite and deposited near the shore of a prehistoric sea may become cemented by calcium or iron in the water to become a solid mass called sandstone. Similarly, clays may be compacted into shale. Other important sedimentary rocks are listed in Table 2.1, along with their dominant minerals. The resistance of a given sedimentary rock to weathering is determined by its particular dominant minerals and by the cementing agent. Because most of what is presently dry land was at some time in the past covered by water, sedimentary rocks are the most common type of rock encountered, covering about 75% of the Earth's land surface.

Metamorphic rocks are formed from other rocks by a process of change termed "metamorphism." As Earth's continental plates shift, and sometimes collide, forces are generated that can uplift great mountain ranges or cause huge layers of rock to be pushed deep into the crust. These movements subject igneous and sedimentary rock masses to tremendous heat and pressure. These forces may slowly compress and partially remelt and distort the rocks, as well

Table 2.1
SOME OF THE MORE IMPORTANT SEDIMENTARY AND METAMORPHIC ROCKS AND THE MINERALS COMMONLY DOMINANT IN THEM

	Type of Rock	
Dominant Mineral	**Sedimentary**	**Metamorphic**
Calcite ($CaCO_3$)	Limestone	Marble
Dolomite ($CaCO_3 \cdot MgCO_3$)	Dolomite	Marble
Quartz (SiO_2)	Sandstone	Quartzite
Clays	Shale	Slate
Variable, silicates	Conglomerate[a]	Gneiss[b]
Variable, silicates		Schist[b]

[a]Small stones of various mineralogical makeup are cemented into conglomerate.
[b]The minerals present are determined by the original rock, which has been changed by metamorphism. Primary minerals present in the igneous rocks commonly dominate these rocks, although some secondary minerals are also present.

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as break the bonds holding the original minerals together. Recrystallization during metamorphism may produce new (usually larger) crystals of the same minerals, or elements from the original minerals may recombine to form new minerals. Igneous rocks like granite may be modified to form gneiss, a metamorphic rock in which light and dark minerals have been reoriented into bands (Figure 2.3, *right*). Sedimentary rocks, such as limestone and shale, may be metamorphosed to marble and slate, respectively (Table 2.1). Slate may be further metamorphosed into phyllite or schist, which typically features mica crystallized during metamorphism.

Metamorphic rocks are usually harder and more strongly crystalline than the sedimentary rocks from which they formed. The particular minerals that dominate a given metamorphic rock influence its resistance to chemical weathering (see Table 2.2 and Figure 2.1).

Weathering: A General Case

Weathering is a biochemical process that involves both destruction and synthesis. Moving from left to right in the weathering diagram (Figure 2.4), the original rocks and minerals are destroyed by both *physical disintegration* and *chemical decomposition*. Without appreciably affecting their composition, physical disintegration breaks down rock into smaller rocks and eventually into sand and silt particles that are commonly made up of individual minerals. Simultaneously, the minerals decompose chemically, releasing soluble materials and synthesizing new minerals, some of which are resistant end products. New minerals form either by minor chemical alterations or by complete chemical breakdown of the original mineral and resynthesis of new minerals. During the chemical changes, particle size continues to decrease, and constituents continue to dissolve in the aqueous weathering solution. The dissolved substances may recombine into new (secondary) minerals, may leave the profile in drainage water, or may be taken up by plant roots.

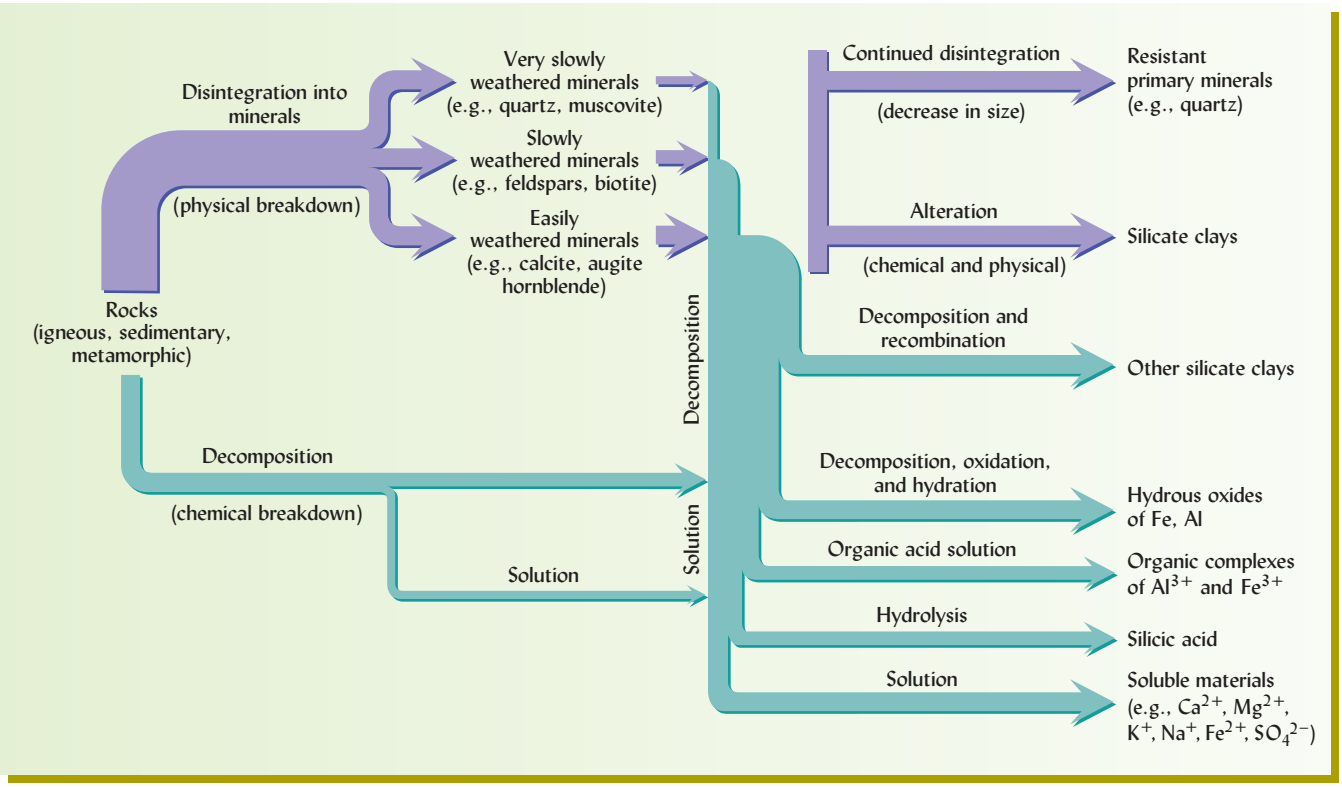

Figure 2.4 *Pathways of weathering that occur under moderately acid conditions common in humid temperate regions. The disintegration of rocks into small individual mineral grains is a physical process, whereas decomposition, recombination, and solution are chemical processes. Alteration of minerals involves both physical and chemical processes. Note that resistant primary minerals, newly synthesized secondary minerals, and soluble materials are products of weathering. In arid regions the physical processes predominate, but in humid tropical areas decomposition and recombination are most prominent.*

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Table 2.2
SELECTED PRIMARY AND SECONDARY MINERALS FOUND IN SOILS LISTED IN ORDER OF DECREASING RESISTANCE TO WEATHERING UNDER CONDITIONS COMMON IN HUMID TEMPERATE REGIONS

Primary Minerals		Secondary Minerals		
		Goethite	$FeOOH$	Most resistant
		Hematite	Fe_2O_3	↑
		Gibbsite	$Al_2O_3 \cdot 3H_2O$	
Quartz	SiO_2			
		Clay minerals	Al silicates	
Muscovite	$KAl_3Si_3O_{10}(OH)_2$			
Microcline	$KAlSi_3O_8$			
Orthoclase	$KAlSi_3O_8$			
Biotite	$KAl(Mg,Fe)_3Si_3O_{10}(OH)_2$			
Albite	$NaAlSi_3O_8$			
Hornblende[a]	$Ca_2Al_2Mg_2Fe_3Si_6O_{22}(OH)_2$			
Augite[a]	$Ca_2(Al,Fe)_4\ (Mg,Fe)_4Si_6O_{24}$			
Anorthite	$CaAl_2Si_2O_8$			
Olivine	$Mg,FeSiO_4$			
		Dolomite[b]	$CaCO_3 \cdot MgCO_3$	
		Calcite[b]	$CaCO_3$	↓
		Gypsum	$CaSO_4 \cdot 2H_2O$	Least resistant

[a]The given formula is only approximate since the mineral is so variable in composition.
[b]In semiarid grasslands, dolomite and calcite are more resistant to weathering than suggested because of low rates of acid weathering.

Three groups of minerals that remain in well-weathered soils are shown on the right side of Figure 2.4: (1) silicate clays, (2) very resistant end products, including iron and aluminum oxide clays, and (3) very resistant primary minerals, such as quartz. In highly weathered soils of humid tropical and subtropical regions, the oxides of iron and aluminum, and certain silicate clays with low Si/Al ratios, predominate because most other constituents have been broken down and removed (see Table 2.3).

Physical Weathering (Disintegration)

Temperature. Rocks exposed to sunlight heat up during the day and cool down at night, causing alternate expansion and contraction of their constituent minerals. As some minerals expand more than others, temperature changes set up differential stresses that eventually cause the rock to crack apart.

Because the outer surface of a rock is often warmer or colder than the more protected inner portions, some rocks may weather by ***exfoliation***—the peeling away of outer layers (Figure 2.5). This process may be sharply accelerated if ice forms in the surface cracks. When water freezes, it expands with a force of about 1465 Mg/m^2, disintegrating huge rock masses (Figure 2.6, *right*) and dislodging mineral grains from smaller fragments.

Abrasion by Water, Ice, and Wind. When loaded with sediment, water has tremendous cutting power (Figure 2.6, *left*), as is amply demonstrated by the gorges, ravines, and valleys around the world. The rounding of riverbed rocks and beach sand grains is further evidence of the abrasion that accompanies water movement.

Windblown dust and sand also can wear down rocks by abrasion, as can be seen in the many picturesque rounded rock formations in certain arid regions. In glacial areas, huge moving ice masses embedded with soil and rock fragments grind down rocks in their path and carry away large volumes of material.

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Table 2.3
PARTIAL ELEMENTAL ANALYSIS OF A GRANITE GNEISS ROCK AND THE B-HORIZON OF A MATURE SOIL DEVELOPED FROM THAT ROCK UNDER FOREST VEGETATION IN A WARM, HUMID CLIMATE

Note that during weathering and soil formation there was a relative loss of calcium, sodium, potassium, and silicon, but a relative increase in iron, aluminum, and copper. A declining ratio of silicon to aluminum is considered an indicator of more complete weathering.

	Analysis, mg/g		
Element[a]	In Rock	In Soil B Horizon	Change, %
Ca	27.2	0.184	–99
Na	36.2	0.197	–99
Mg	5.28	1.38	–74
P	0.496	0.383	–23
K	9.79	7.88	–20
Si	324	308	–5
Al	88.1	128	+45
Fe	20.8	40.1	+93
Cu	0.003	0.022	+633
Si/Al	3.7	2.4	–35

[a]Elemental analysis is given here, although many geologists report these values in terms of the oxides of the element: for example, 166.4 mg Al_2O_3, rather than 88.1 mg Al. (Selected and calculated by author from data in Richter and Markewitz [2001])

Plants and Animals. Plant roots sometimes enter cracks in rocks and pry them apart, resulting in some disintegration. Burrowing animals may also help disintegrate rock somewhat. However, such influences are of little importance in producing parent material when compared to the drastic physical effects of water, ice, wind, and temperature change.

Biogeochemical Weathering

While physical weathering is accentuated in very cold or very dry environments, chemical reactions are most intense where the climate is wet and hot. However, both types of weathering

Figure 2.5 *Two illustrations of rock weathering.* (Left) *An illustration of concentric weathering called* exfoliation. *A combination of physical and chemical processes stimulates the mechanical breakdown, which produces layers that appear much like the leaves of a cabbage.* (Right) *Concentric bands of light and dark colors indicate that chemical weathering (oxidation and hydration) has occurred from the outside inward, producing iron compounds that differ in color.* (Right photo courtesy of Ray R. Weil)

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Figure 2.6 *Effects of water on weathering and the breakdown of rock.* (Left) *The V-like notch carved by water in this sandstone cliff in Montana, USA, is evidence of the cutting power of water laden with sediment. The cave below the notch was carved by eddies under the ancient waterfall.* (Right) *The expansion of water as it freezes has broken up these Appalachian sedimentary rocks into ever smaller fragments.* (Photos courtesy of Ray R. Weil)

occur together, and each tends to accelerate the other. For example, physical abrasion (rubbing together) decreases the size of particles and therefore increases their surface area, making them more susceptible to rapid chemical reactions.

Chemical weathering is enhanced by such *geological* agents as the presence of water and oxygen, as well as by such *biological* agents as the acids produced by microbial and plant-root metabolism. That is why the term **biogeochemical weathering** is often used to describe the process. The various agents act in concert to convert primary minerals (e.g., feldspars and micas) to secondary minerals (e.g., clays and carbonates) and release plant nutrient elements in soluble forms (see Figure 2.7). Note the importance of water in each of the six basic types of chemical weathering reactions discussed in the following.

Hydration. Intact water molecules may bind to a mineral by a process called ***hydration***.

$$\underset{\text{Hematite}}{5Fe_2O_3} + \underset{\text{Water}}{9H_2O} \xrightarrow{\text{Hydration}} \underset{\text{Ferrihydrite}}{Fe_{10}O_{15} \cdot 9H_2O} \qquad (2.1)$$

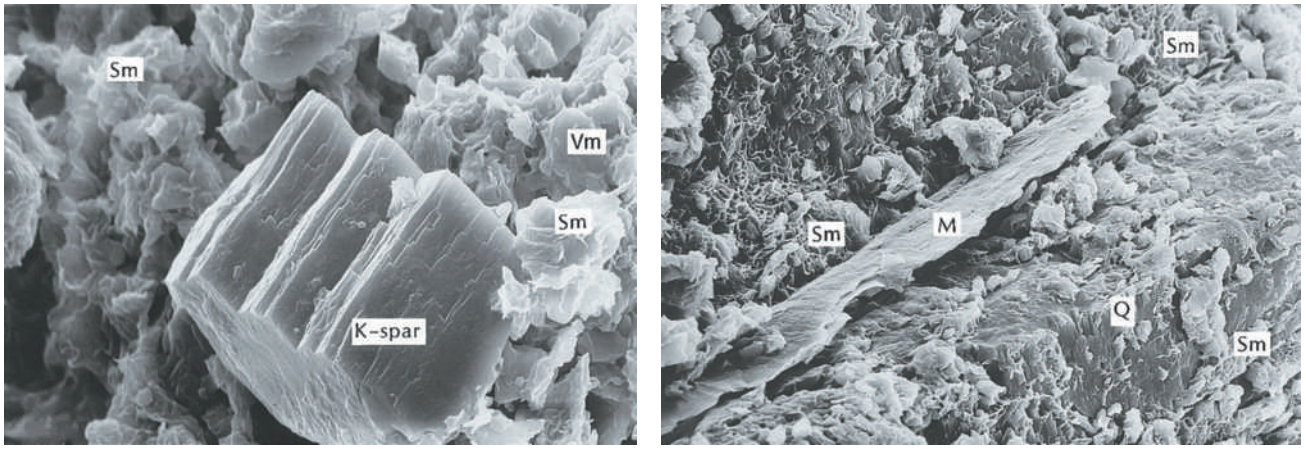

Figure 2.7 *Alteration of primary minerals to form clays and other secondary minerals .* (Left) *Scanning electron micrograph illustrating silicate clay formation from weathering of a granite rock. Potassium feldspar (K-spar) is surrounded by the silicate clays, smectite (Sm), and vermiculite (Vm).* (Right) *A microscopic image of weathered basalt rock obtained using crossed polarized light. The image shows replacement of pyroxene (blue colored primary mineral labeled Px) by smectite (greenish brown, Sm) and hematite (reddish, Hm). Tiny crystals of plagioclase (Pg) also exhibit alteration to smectite (Sm). Note the 30-fold difference in scale between the two images.* (Courtesy of Dr. J. Reed Glasmann, Willamette Geological Service, Philomath, OR)

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Hydrated oxides of iron and aluminum (e.g., $Al_2O_3 \cdot 3H_2O$) exemplify common products of hydration reactions.

Hydrolysis. In hydrolysis reactions, water molecules split into their hydrogen and hydroxyl components, and the hydrogen often replaces a cation from the mineral structure. A simple example is the action of water on microcline, a potassium-containing feldspar.

$$\underset{\text{(solid)}}{KAlSi_3O_8} + \underset{\text{Water}}{H_2O} \xrightleftharpoons{\text{Hydrolysis}} \underset{\text{(solid)}}{HAlSi_3O_8} + \underset{\text{(solution)}}{K^+ + OH^-} \tag{2.2}$$

$$\underset{\text{(solid)}}{2HAlSi_3O_8} + \underset{\text{Water}}{11H_2O} \xrightleftharpoons{\text{Hydrolysis}} \underset{\text{(solid)}}{Al_2O_3} + \underset{\text{(solution)}}{6H_4SiO_4} \tag{2.3}$$

The potassium released is soluble and is subject to adsorption by soil colloids, uptake by plants, and removal in the drainage water. Likewise, the silicic acid (H_4SiO_4) is soluble. It can be removed slowly in drainage water, or it can recombine with other compounds to form secondary minerals such as the silicate clays.

Dissolution. Water is capable of dissolving many minerals by hydrating the cations and anions until they become dissociated from each other and surrounded by water molecules. Gypsum dissolving in water provides an example.

$$\underset{\text{(solid)}}{CaSO_4 \cdot 2H_2O} + \underset{\text{Water}}{2H_2O} \xrightleftharpoons{\text{Dissolution}} \underset{\text{(solution)}}{Ca^{2+} + SO_4^{2-}} + \underset{\text{Water}}{4H_2O} \tag{2.4}$$

Acid Reactions. Weathering is accelerated by the presence of acids, which increase the activity of hydrogen ions in water. For example, when carbon dioxide dissolves in water (a process enhanced by microbial and root respiration) the carbonic acid (H_2CO_3) produced hastens the chemical dissolution of calcite in limestone or marble, as illustrated when the following reactions go to the right:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \tag{2.5}$$

$$\underset{\text{Carbonic acid}}{H_2CO_3} + \underset{\text{Calcite (solid)}}{CaCO_3} \xrightleftharpoons{\text{Carbonation}} \underset{\text{(solution)}}{Ca^{2+}} + \underset{\text{(solution)}}{2HCO_3^-} \tag{2.6}$$

Soils also contain nitric acid (HNO_3), sulfuric acid (H_2SO_4), and many organic acids and hydrogen ions associated with clays—all of which can react with soil minerals.

Oxidation–Reduction. Minerals that contain iron, manganese, or sulfur are especially susceptible to oxidation–reduction reactions. Iron is usually laid down in primary minerals in the divalent Fe(II) (ferrous) form. When rocks containing such minerals are exposed to air and water during soil formation, the iron is easily oxidized (loses an electron) and becomes trivalent Fe(III) (ferric). If iron is oxidized from Fe(II) to Fe(III), the change in valence and ionic radius causes destabilizing adjustments in the crystal structure of the mineral.

In other cases, Fe(II) may be released from the mineral and almost simultaneously oxidized to Fe(III). For example, the hydration of olivine releases ferrous oxide, which may be oxidized immediately to ferric oxyhydroxide (goethite).

$$\underset{\substack{\text{Olivine}\\\text{(solid)}}}{3MgFeSiO_4} + \underset{\text{Water}}{2H_2O} \xrightleftharpoons{\text{Hydrolysis}} \underset{\substack{\text{Serpentine}\\\text{(solid)}}}{H_4Mg_3Si_2O_9} + \underset{\text{(solution)}}{SiO_2} + \underset{\substack{\text{Fe(II) oxide}\\\text{(solid)}}}{3FeO} \tag{2.7}$$

$$\underset{\substack{\text{Fe(II)}\\\text{oxide}}}{4FeO} + O_2 + 2H_2O \underset{\text{Hydrolysis}}{\overset{\text{Oxidation}}{\rightleftharpoons}} \underset{\substack{\text{Goethite}\\\text{[Fe(III) oxyhydroxide]}}}{4FeOOH} \tag{2.8}$$

The oxidation and/or removal of iron during weathering is often made visible by changes in the colors of the resulting altered minerals (see Figure 2.5, *right*).

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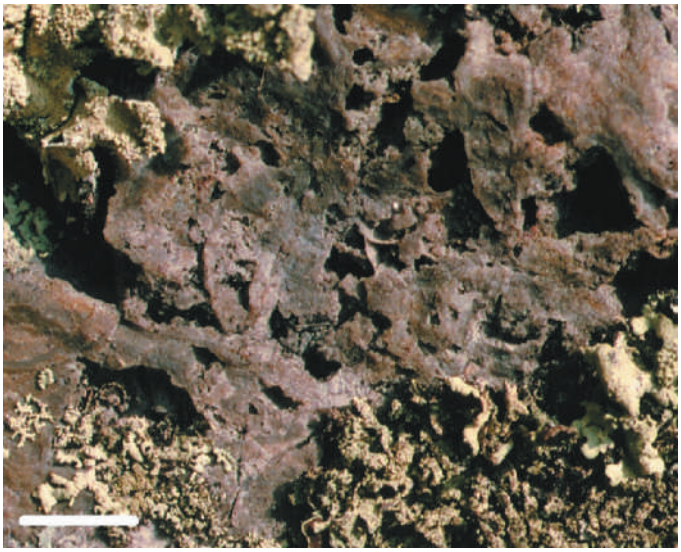

Figure 2.8 *First stages of soil development: Biochemical weathering of a rock under the influence of mosses and lichen (a symbiotic combination of algae and fungi). Lichens are especially effective at pioneering inhospitable sites. The algal component provides energy-rich compounds from photosynthesis, whereas the fungal partner unlocks mineral nutrients from the rock. The fungus produces organic acids that break down the rock by hydrolysis and complexation reactions. Note the pitted surface of the rock where a lichen mat was pulled away to expose the weathering rock surface. The resulting loose mineral material and soluble nutrients, in conjunction with trapped dust and organic debris left by the lichen, will eventually provide a medium for the growth of higher plants. These in turn will further accelerate the process of soil formation. White bar is 1 cm.* (Photo courtesy of Ray R. Weil)

Complexation. Soil biological processes produce organic acids such as oxalic, citric, and tartaric acids, as well as larger organic acid molecules (see Section 12.4). In addition to providing H^+ ions that help solubilize aluminum and silicon, they also form organic complexes with Al^{3+} ions from within the structure of silicate minerals, causing these minerals to further disintegrate. In the following example, oxalic acid forms a soluble complex with aluminum from the mineral, muscovite. As this reaction proceeds to the right, it destroys the muscovite structure and releases dissolved ions of the plant nutrient, potassium.

$$\underset{\substack{\text{Muscovite}\\\text{(solid)}}}{K_2[Si_6Al_2]Al_4O_{20}(OH)_4} + \underset{\text{Oxalic acid}}{6C_2O_4H_2} + \underset{\text{Water}}{8H_2O} \xrightleftharpoons{\text{Complexation}} \underset{\substack{\text{Potassium hydroxide}\\\text{(solution)}}}{2K^+ + 8OH^-} + \underset{\substack{\text{Complex}\\\text{(solution)}}}{6C_2O_4Al^+} + \underset{\text{(solution)}}{6Si(OH)_4^0} \qquad (2.9)$$

Had there been no living organisms on Earth, the chemical weathering processes we have just outlined would probably have preceded 1000 times more slowly, with the result that little, if any, soil would have developed on our planet.

Integrated Weathering Processes. The various chemical weathering processes occur simultaneously and are interdependent. For example, hydrolysis of a given primary mineral may release ferrous iron [Fe(II)] that is quickly oxidized to the ferric [Fe(III)] form, which, in turn, is hydrolized to give a hydrous oxide of iron. Hydrolysis or complexation also may release soluble cations, silicic acid, and aluminum or iron compounds. In humid environments, some of the soluble cations and silicic acid are likely to be lost from the weathering mass in drainage waters. The released substances can also be recombined to form silicate clays and other secondary silicate minerals. In this manner, the biochemical processes of weathering transform primary geologic materials into the compounds of which soils are made (Figure 2.8).

2.2 WHAT ENVIRONMENTAL FACTORS INFLUENCE SOIL FORMATION?[4]

We learned in Chapter 1 that *the soil* is a collection of *individual soils*, each with distinctive profile characteristics. This concept of soils as organized natural bodies derived initially from late 19th-century field studies by a team of brilliant Russian soil scientists led by V. V. Dukochaev. They noted similar profile layering in soils hundreds of kilometers apart, provided that the climate and vegetation were similar at the two locations. Such observations

[4]Many of our modern concepts concerning the factors of soil formation are derived from the work of Hans Jenny (1941 and 1980) and E. W. Hilgard (1921), American soil scientists whose books are considered classics in the field.

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and much careful subsequent field and laboratory research led to the recognition by Hans Jenny of five major environmental factors that control the formation of soils. In 1941 he published the now classical state factor model of soil formation:

$$S_i = f(cl,o,r,p,t) \tag{2.10}$$

which tells us that a particular soil property, S_i, will be determined by a function of five factors that describe the environment in which the soil occurs:

1. ***cl**: climate* (primarily precipitation and temperature)
2. ***o**: organisms* (biota, especially native vegetation, microbes, soil animals, and increasingly, human beings)
3. ***r**: relief or topography* (slope, aspect, and landscape position)
4. ***p**: parent materials* (geological or organic precursors to the soil)
5. ***t**: time* (the period of time since the parent materials began to undergo soil formation)

Soils are often defined in terms of these factors as *dynamic natural bodies having properties derived from the combined effects of* ***climate*** *and* ***biotic activities****, as modified by* ***topography****, acting on* ***parent materials*** *over periods of* ***time****.*

We will now examine how each of these five factors affects the outcome of soil formation. However, as we do, we must keep in mind that these factors do not exert their influences independently. Indeed, interdependence is the rule. For example, contrasting climatic regimes are likely to be associated with contrasting types of vegetation, and perhaps differing topography and parent material as well. Nonetheless, in certain situations one of the factors has had the dominant influence in determining differences among a set of soils. Soil scientists refer to such a set of soils as a ***lithosequence***, ***climosequence***, ***biosequence***, ***toposequence***, or ***chronosequence***.

2.3 PARENT MATERIALS

Geological processes have brought to the Earth's surface numerous parent materials in which soils form (Figure 2.9). The nature of the parent material profoundly influences soil characteristics. For example, a soil might inherit a sandy texture (see Section 4.2) from a coarse-grained,

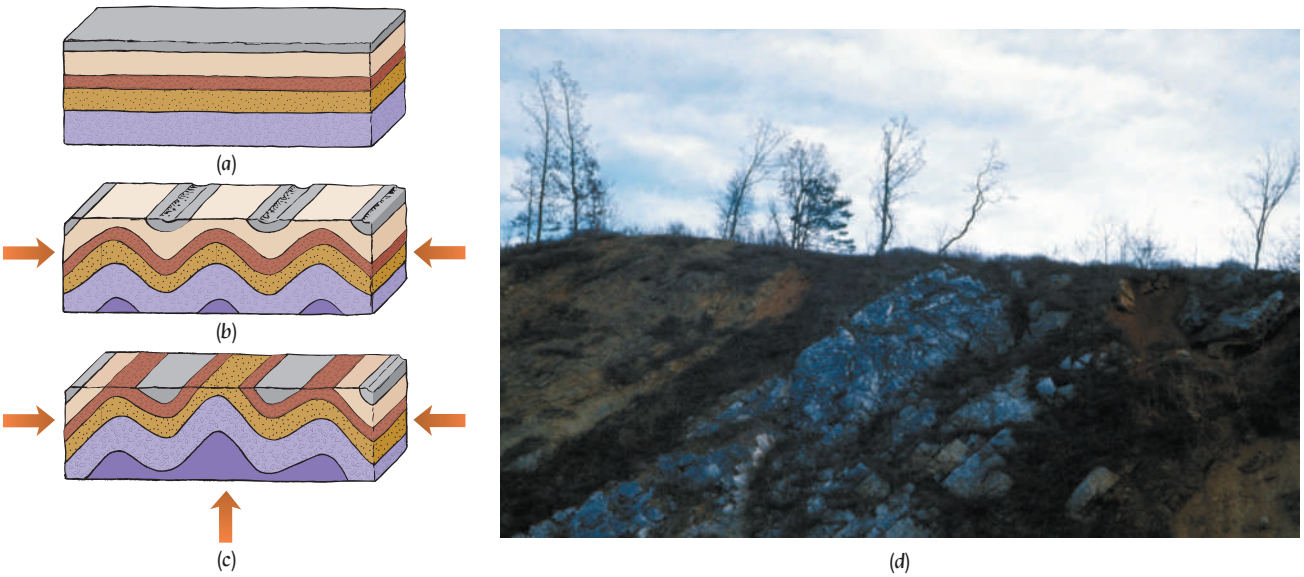

Figure 2.9 *Diagrams showing how geological processes have brought different rock layers to the surface in a given area.* (a) *Unaltered layers of sedimentary rock with only the uppermost layer exposed.* (b) *Lateral geological pressures deform the rock layers through a process called* crustal warping. *At the same time, erosion removes much of the top layer, exposing part of the first underlying layer.* (c) *Localized upward pressures further reform the layers, thereby exposing two more underlying layers. As these four rock layers are weathered, they give rise to the parent materials on which different kinds of soils can form.* (d) *Crustal warping that lifted up the Appalachian Mountains of the eastern United States tilted these sedimentary rock formations that were originally laid down horizontally. This deep road cut in Virginia, USA, illustrates the abrupt change in soil parent material (lithosequence) as one walks along the ground surface at the top of this photograph.* (Photo courtesy of Ray R. Weil)

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quartz-rich parent material such as granite or sandstone. Soil texture, in turn, helps control the percolation of water through the soil profile, thereby affecting the translocation of fine soil particles and plant nutrients.

The chemical and mineralogical composition of parent material also influences both chemical weathering and the natural vegetation. For example, the presence of limestone in parent material will slow the development of acidity that typically occurs in humid climates.

The parent material may contain varying amounts and types of clay minerals, perhaps from a previous weathering cycle. The nature of the parent material greatly influences the kinds of clays that can develop as the soil evolves (see Section 8.5). In turn, the nature of the clay minerals present markedly affects the kind of soil that develops.

Classification of Parent Materials

Inorganic parent materials can either be formed in place as residual material weathered from the rock below, or they can be transported from one location and deposited at another (Figure 2.10). In wet environments (such as swamps and marshes), incomplete decomposition may allow organic parent materials to accumulate from the residues of many generations of vegetation. Although it is their chemical and physical properties that most influence soil development, parent materials are often classified with regard to the mode of placement in their current location, as seen on the right side of Figure 2.10.

Although people sometimes refer to *organic soils*, *glacial soils*, *alluvial soils*, and so forth, these terms are quite nonspecific because parent material properties vary widely within each group and because the effect of parent material is modified by the influence of climate, organisms, topography, and time.

Residual Parent Material

Residual parent material develops in place from weathering of the underlying rock. In stable landscapes it may have experienced long and possibly intense weathering. Where the climate is warm and very humid, residual parent materials are typically thoroughly leached and oxidized, and they show the red and yellow colors of various oxidized iron compounds. In cooler and especially drier climates, the color and chemical composition of residual parent material tends to resemble more closely the rock from which it formed (Figure 2.11).

Residual materials are widely distributed on all continents. The physiographic map of the United States (Figure 2.12) shows nine great provinces where residual materials are prominent (shades of *purple* on the map). A great variety of soils occupy the regions covered by residual debris because of the marked differences in the nature of the rocks from which these

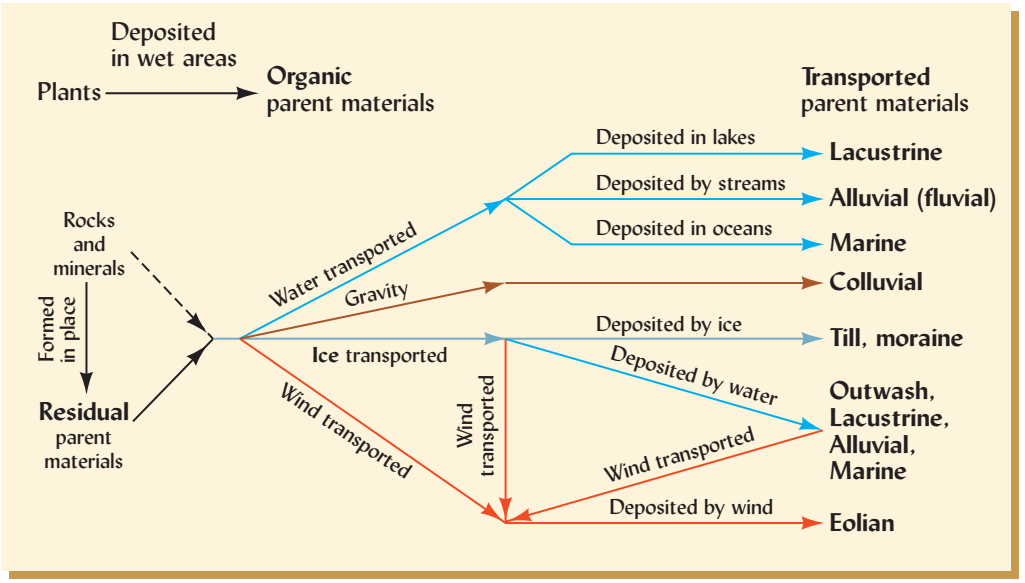

Figure 2.10 *How various kinds of parent material are formed, transported, and deposited.* (Diagram courtesy of N. C. Brady and Ray R. Weil)

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Figure 2.11 *Rock weathering in a humid tropical Liberia* (left) *and in subhumid, temperate Kansas, USA* (right). *In the tropical soil weathering has been deep and the gray rock (not seen) has radically changed in color and composition (due to residual iron oxides). Compare this to the shallower regolith and similar gray-brown colors of the rock and parent material in the subhumid temperate soil. Scale in meters.* (Photos courtesy of Ray R. Weil)

materials evolved. The varied soils are also a reflection of wide differences in other soil-forming factors, such as climate and vegetation (Sections 2.4 and 2.5).

Colluvial Debris

Colluvial debris, or **colluvium**, is made up of poorly sorted rock fragments detached from the heights above and carried downslope, mostly by gravity, assisted in some cases by frost action or water. Rock fragment (talus) slopes, cliff rock debris (detritus), and similar heterogeneous materials are examples that can contribute to avalanches on steep slopes.

Colluvial parent materials are frequently coarse and stony because physical rather than chemical weathering has been dominant. Stones, gravel, and fine materials are interspersed (not layered), and the coarse fragments are rather angular (Figure 2.13). Packing voids, spaces created when tumbling rocks come to rest against each other (sometimes at precarious angles), help account for the easy drainage of many colluvial deposits and also for their tendency to be unstable and prone to slumping and landslides, especially if disturbed by excavations.

Alluvial Stream Deposits

There are three general classes of alluvial deposits: *floodplains*, *alluvial fans*, and *deltas*. They will be considered in that order.

Floodplains. During flooding, a swollen stream will inundate the adjacent flat land known as the floodplain. The flood waters deposit sediments on the floodplain, laying down the coarser materials near the river channel where the water flows deeper, faster and with more turbulence. Finer materials settle out in the calmer flood waters farther from the channel. Each major flooding episode lays down a distinctive layer of sediment, creating the stratification that characterizes alluvial soils (Figure 2.14).

If, over a period of time, there is a change in grade, a stream may cut down through its already well-formed alluvial deposits. This cutting action leaves **terraces** above the floodplain

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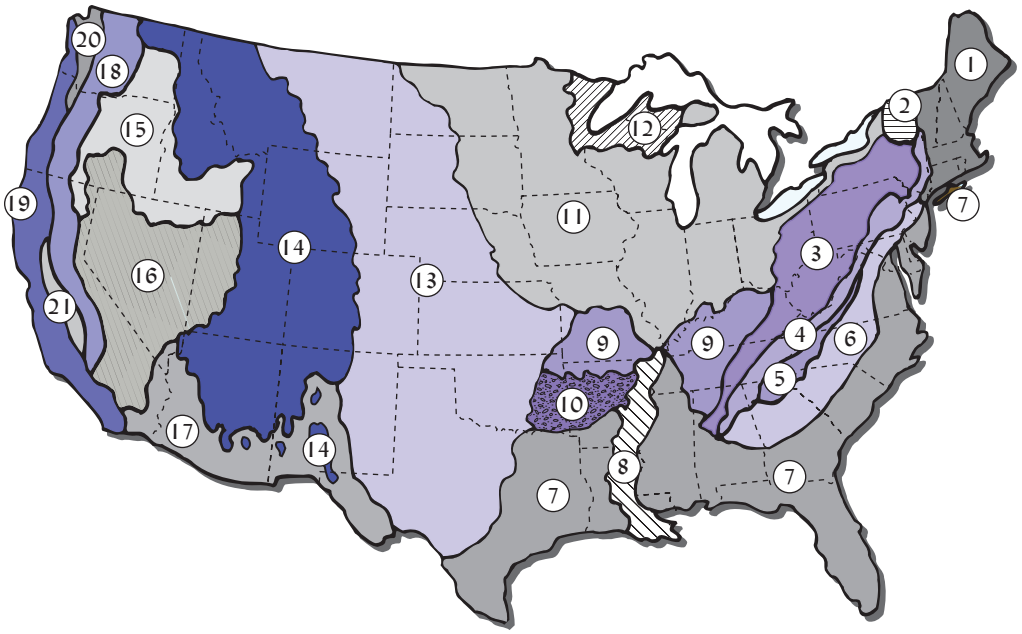

Figure 2.12 *Generalized physiographic and regolith map of the United States. In the key, major areas of residual parent material are italicized and shown in shades of purple.*

1. New England: mostly glaciated metamorphic rocks.
2. Adirondacks: glaciated metamorphic and sedimentary rocks.
3. *Appalachian Mountains and plateaus:* shales and sandstones.
4. *Limestone valleys and ridges:* mostly limestone.
5. Blue Ridge Mountains: sandstones and shales.
6. *Piedmont plateau:* metamorphic rocks.
7. Atlantic and Gulf coastal plain: unconsolidated sediments; sands, clays, and silts.
8. Mississippi floodplain and delta: alluvium.
9. *Limestone uplands:* mostly limestone and shale.
10. *Sandstone uplands:* mostly sandstone and shale.
11. Central lowlands: mostly glaciated sedimentary rocks with till and loess.
12. Superior uplands: glaciated metamorphic and sedimentary rocks.
13. *Great Plains region:* sedimentary rocks.
14. *Rocky Mountain region:* sedimentary, metamorphic, and igneous rocks.
15. Northwest intermountain: mostly igneous rocks; loess in river basins.
16. Great Basin: gravels, sands, alluvial fans; igneous and sedimentary rocks.
17. Southwest arid region: gravel, sand, and other debris of desert and mountain.
18. *Sierra Nevada and Cascade mountains:* igneous and volcanic rocks.
19. *Pacific Coast province:* mostly sedimentary rocks.
20. Puget Sound lowlands: glaciated sedimentary rocks.
21. California central valley: alluvium and outwash.

Figure 2.13 *A productive soil formed in colluvial parent material in the Appalachian Mountains of the eastern United States. The ridge in the background was at one time much taller, but material from the crest tumbled downslope and came to rest in the configuration seen in the soil profile. Note the unstratified mix of particle sizes and the rather angular nature of the coarse fragments.* (Photo courtesy of Ray R. Weil)

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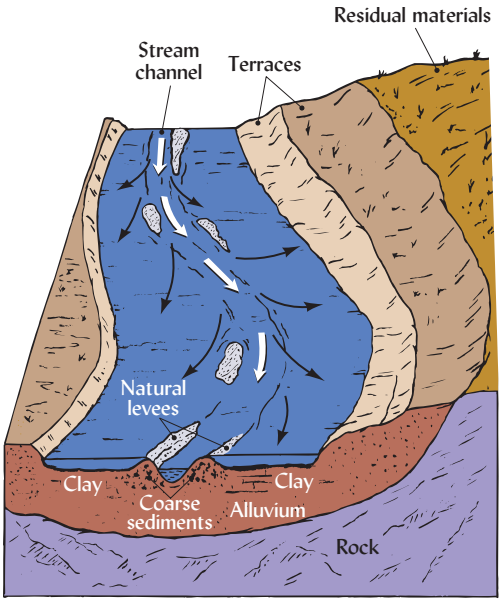
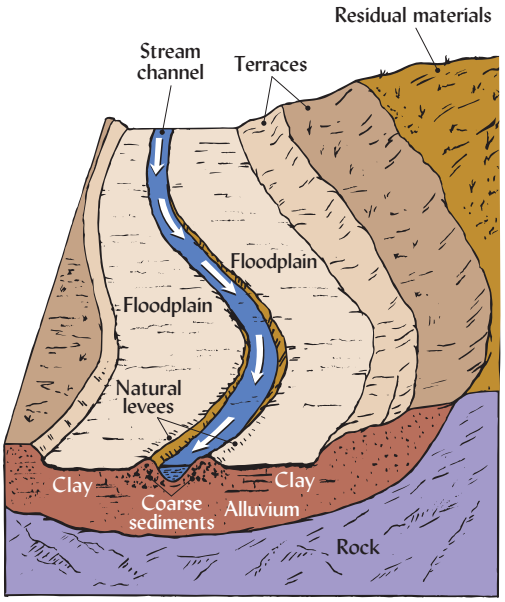


(a)



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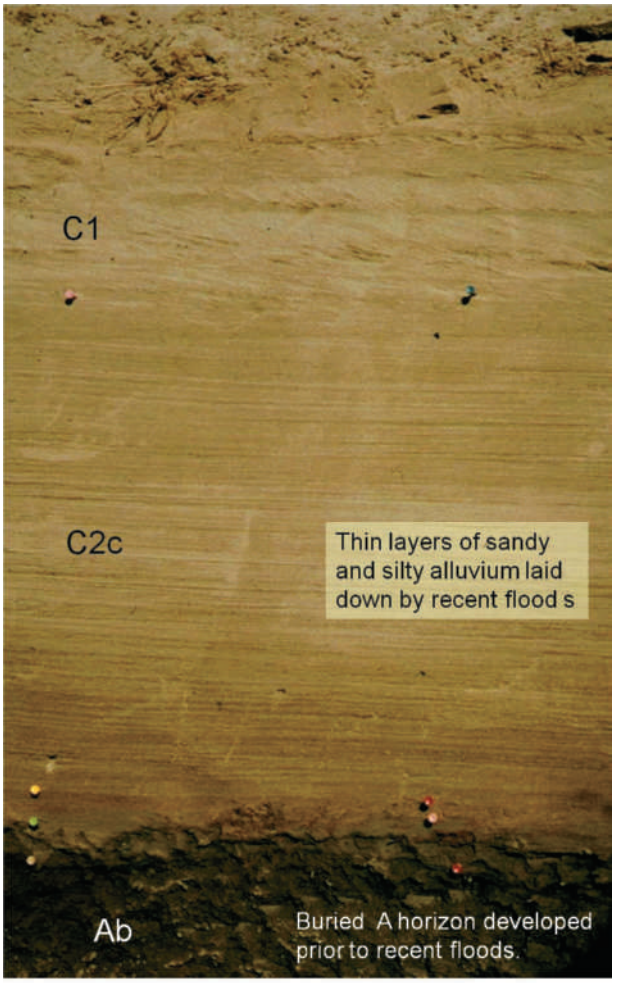

(c)

Figure 2.14 *Floodplain development.* (a) *A stream at flood stage has overflowed its banks and is depositing sediment in the floodplain. The coarser particles are deposited nearest the stream channel where the water is flowing most rapidly, whereas the finer particles settle out where the water is moving more slowly.* (b) *After the flood the sediments are in place and vegetation is growing.* (c) *Upper 120 cm of a profile of a soil on the Mississippi River floodplain in the United States showing contrasting thin layers of sand and silt sediments in the new C horizon that was laid down over an older A horizon. Each layer resulted from a separate flooding episode.* (Diagrams and photo courtesy of Ray R. Weil)

on one or both sides. Some river valleys feature two or more terraces at different elevations, each reflecting a past period of alluvial deposition and stream cutting.

Major areas of alluvial parent materials are found along the Nile River in Egypt and Sudan; the Euphrates, Ganges, Indus, Brahmaputra, and Hwang Ho river valleys of Asia; and the Amazon River of Brazil. The floodplain along the Mississippi River is the largest in the United States (area 8 in Figure 2.12), varying from 30 to 125 km in width. Floodplains of smaller streams also provide parent materials for locally important soil areas.

To some degree, nutrient-rich materials lost by upland soils are deposited on the river floodplain and **delta** (see following). Soils derived from alluvial sediments generally have characteristics seen as desirable for human settlement and agriculture. These characteristics include nearly level topography, proximity to water, high fertility, and high productivity. Although many alluvial soils are well drained, others may require artificial drainage if they are to be used for upland crops or for stable building foundations.

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While alluvial soils are often uniquely suited to forestry and crop production, their use for home sites and urban development should generally be avoided. Unfortunately, the desirable properties of many alluvial soils have led people to build cities and towns on floodplains. As the many disastrous floods of recent years have illustrated, building on a floodplain, no matter how great the investment in flood-control measures, all too often leads to tragic loss of life and property.

In many areas, installation of systems for drainage and flood protection has proven costly and ineffective. Farmers and the general public pay high costs to keep such areas in agricultural or urban uses. Steps are therefore being taken to reestablish the wetland conditions of certain flood-prone agricultural areas that originally were natural wetlands. These and other alluvial soils can provide natural habitats, such as bottomland forests, which produce vast quantities of timber and support a high diversity of birds and other wildlife.

Alluvial Fans. Streams that leave a narrow valley in an upland area and suddenly descend to a much broader valley below deposit sediment in the shape of a fan, as the water spreads out and slows down (see Figure 2.15 and Figure 19.20). The rushing water tends to sort the sediment particles by size, first dropping the gravel and coarse sand, then depositing the finer materials toward the bottom of the alluvial fan.

Alluvial fan debris is found in widely scattered areas in mountainous and hilly regions. The soils derived from this debris often prove very productive, although they may be quite coarse-textured. In the United States, the Sacramento Valley in California and the Willamette Valley in Oregon are examples of large, agriculturally important areas with alluvial fan materials.

Delta Deposits. Much of the finer sediment carried by streams is not deposited in the floodplain but is discharged into the lake, reservoir, or ocean into which the streams flow. Some of the suspended material settles near the mouth of the river, forming a delta. Such delta deposits are by no means universal, being found at the mouths of only a few rivers of the world. A delta often is a continuation of a floodplain (its front, so to speak). It is clayey in nature and is likely to be poorly drained as well.

Delta marshes are among the most extensive and biologically important of wetland habitats. Many of these habitats are today being protected or restored, but civilizations both ancient and modern have also developed important agricultural areas (often specializing in the production of rice) by creating drainage and flood-control systems on the deltas of such rivers as the Amazon, Euphrates, Ganges, Hwang Ho, Mississippi, Nile, Po, and Tigris.

Coastal Sediments

Streams eventually deposit much of their sediment loads in oceans, estuaries, and gulfs. The coarser fragments settle out near the shore and the finer particles at a distance (Figure 2.16). Over long periods of time, these underwater sediments build up, in some cases becoming

Figure 2.15
Characteristically shaped alluvial fan (central foreground of photo) in a valley in central Nevada, USA. Although alluvial fan areas are usually small and sloping, they can develop into productive, well-drained soils. (Photo courtesy of Ray R. Weil)

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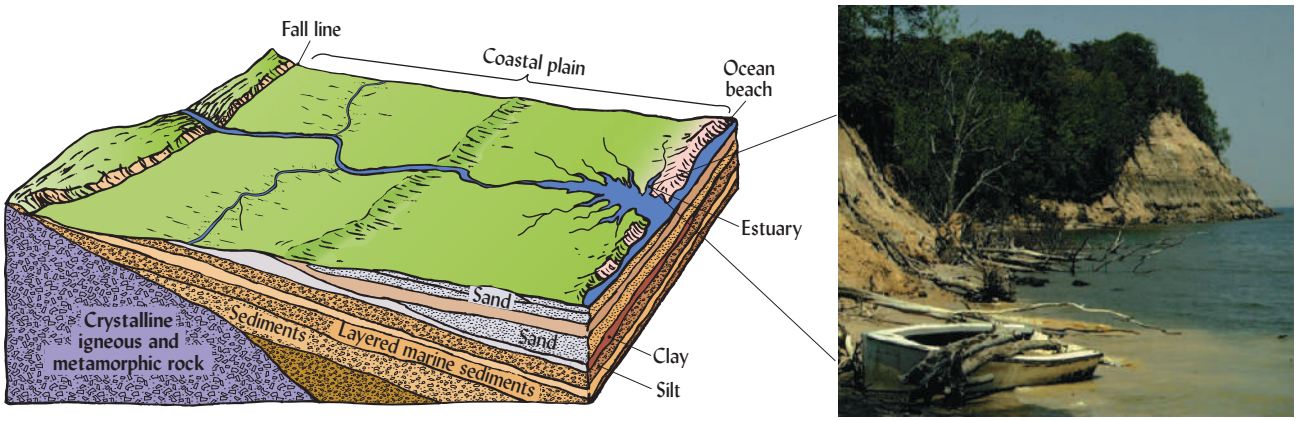

Figure 2.16 *Coastal plain sediments consist of materials laid down in marine waters and washed off interior hills onto coastal areas. The diagram represents the coastal plain of the southeastern United States where such sediments cover older crystalline igneous and metamorphic rocks. Changes in the location of the shoreline and currents over time have resulted in sediment layers consisting alternately of fine clay, silts, coarse sands, and gravels. The photo shows such layering in coastal marine sediments along the Chesapeake Bay in Maryland, USA.* (Diagram and photo courtesy of Ray R. Weil)

hundreds of meters thick. Changes in the relative elevations of sea and land may later raise these marine deposits above sea level, creating a coastal plain. The deposits are then subject to a new cycle of weathering and soil formation.

A coastal plain usually has only moderate slopes, being more level in the low-lying parts nearer the coastline and more hilly farther inland, where streams and rivers flowing down the steeper grades have more deeply dissected the landscape. The land surface in the lower coastal portion may be only slightly above the water table during part of the year, so wetland forest and marsh vegetation often dominate areas of such parent materials.

Marine and other coastal deposits are quite variable in texture. Some are sandy, as is the case in much of the Atlantic seaboard Coastal Plain in the United States. Others are high in clay, as are deposits found in the Atlantic and Gulf Coastal Flatwoods. Where streams have cut down through layers of marine sediments (as in the detailed block diagram in Figure 2.16), clays, silts, and sand may be encountered side by side. All of these sediments came from the erosion of upland areas, some of which were highly weathered before the transport took place. However, marine sediments generally have been subjected to soil-forming processes for a shorter period of time than their upland counterparts. As a consequence, the properties of the soils that form are heavily influenced by those of the marine parent materials. Because seawater is high in sulfur, many marine sediments are high in sulfur and go through a period of acid-forming sulfur oxidation at some stage of soil formation (see Sections 9.6 and 13.20).

Parent Materials Transported by Glacial Ice and Meltwaters

During the Pleistocene epoch (about 10^4 to 10^7 years ago), up to 20% of the world's land surface—northern and central Europe, parts of northern Asia, and northern North America—was invaded by a succession of great ice sheets, some more than 1 km thick (Figure 2.17). Present-day glaciers in polar regions and high mountains cover about a third as much area but are not nearly so thick as the glaciers of the Great Pleistocene Ice Age.[5]

In North America, Pleistocene epoch glaciers covered most of what is now Canada, southern Alaska, and the northern part of the contiguous United States. The southernmost extension went down the Mississippi Valley, where the least resistance was met because of the lower and smoother topography.

As the glacial ice pushed forward, it swept away the existing regolith with its soil mantle, rounded the hills, filled in the valleys, and, in some cases, severely ground and gouged the

[5]Though they are much smaller than paleoglaciers, if all present day glaciers were to melt, the world sea level would rise by about 65 m. Current global warming trends are observably accelerating glacier melting and sea level rise, thus threatening many coastal areas around the world with inundation in coming decades.

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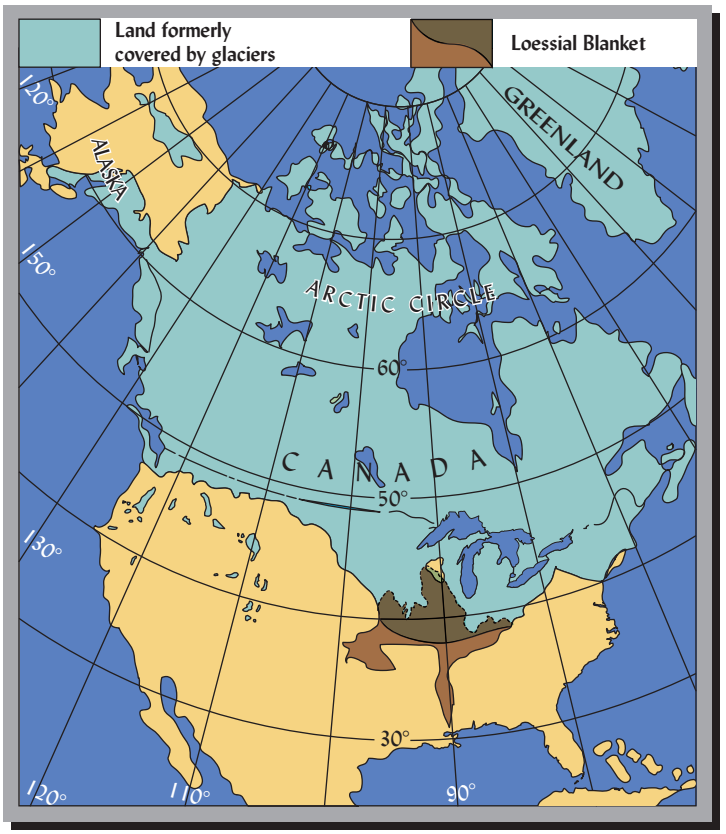

Figure 2.17 *Map of North America showing the greatest extent of the glaciers of the Great Ice Age during the Pleistocene period. Most of the areas then covered by glaciers are now covered by glacial till. A large area in the central United States, partly over the glacial till and partly beyond the extent of the glaciers themselves, is now covered by a blanket of loess generated after the glaciers retreated.* [Map adapted from Schlee (2000)]

underlying rocks. Thus, the glacier became filled with rock and all kinds of unconsolidated materials, carrying great masses of these materials as it pushed ahead (Figure 2.18). Finally, as the ice melted and the glacier retreated, a mantle of glacial debris or drift remained. This provided a new regolith and fresh parent material for soil formation.

Glacial Till and Associated Deposits. The name **drift** is applied to all material of glacial origin, whether deposited by the ice or by associated waters. The materials deposited directly by the ice, called **glacial till**, are heterogeneous (unstratified) mixtures of debris, which vary in size from boulders to clay. Till (the adjective "glacial" is optional as there is no non-glacial till) may therefore be somewhat similar in appearance to colluvial materials, except that the coarse fragments are more rounded from their grinding journey in the ice, and the deposits are often much more densely compacted because of the great weight of the overlying ice sheets. Much glacial till is deposited in irregular ridges called **moraines**. Figure 2.19 shows how glacial sheets deposited several types of soil parent materials.

Figure 2.18 (left) *Two tongues of a modern-day glacier in Argentina's Los Glaciares National Park and* (right) *a valley carved out by an ancient glacier in the Rocky Mountains of the United States. This U-shaped valley illustrates the work of glaciers in carving out land forms. The glacier left the valley floor covered with glacial till. Some of the material gouged out by the glacier was deposited many kilometers down the valley.* [Photos courtesy of National Aeronautics and Space Administration (NASA), *left* and Ray R. Weil, *right*]

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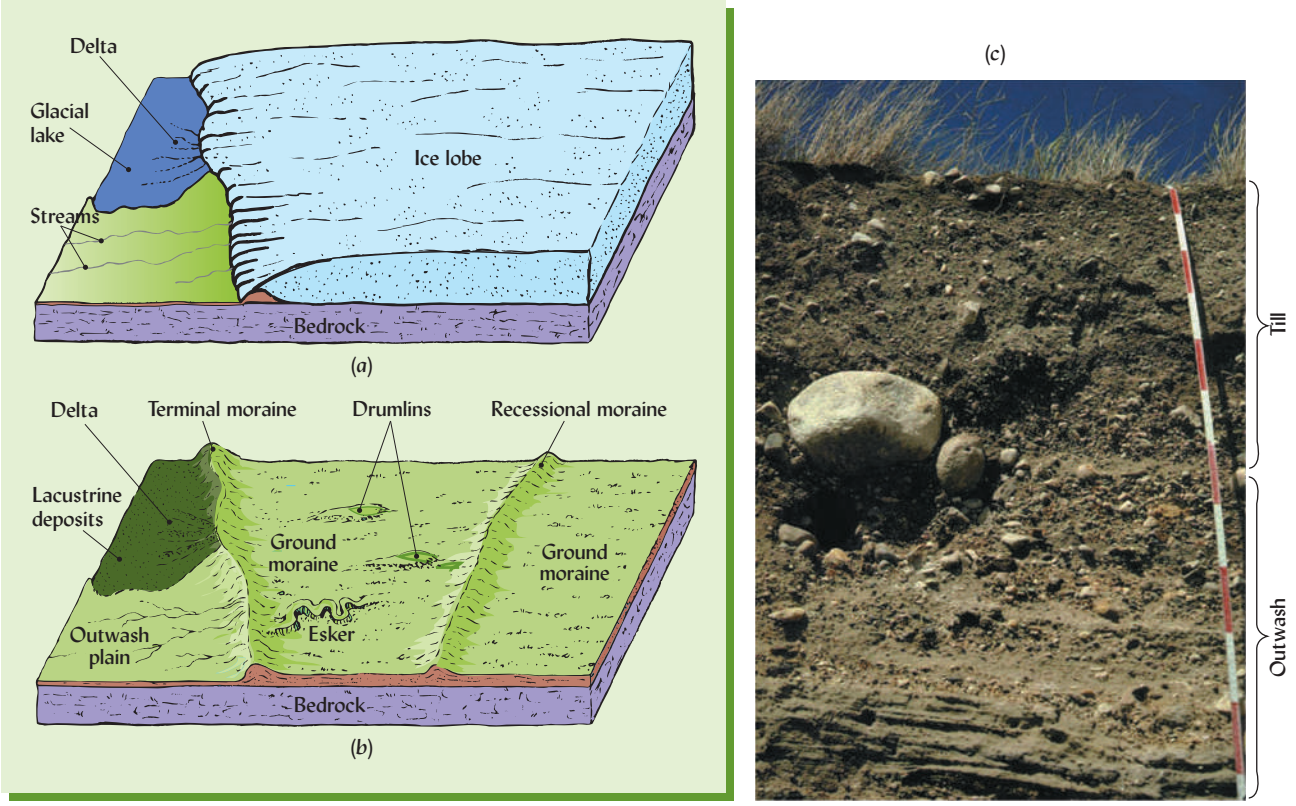

Figure 2.19 *Illustration of how several glacial materials were deposited.* (a) *A glacier ice lobe moving to the left, feeding water and sediments into a glacial lake and streams and building up glacial till near its front.* (b) *After the ice retreats, terminal, ground, and recessional moraines are uncovered along with cigar-shaped hills (drumlins); the beds of rivers that flowed under the glacier (eskers); and lacustrine, delta, and outwash deposits.* (c) *The stratified glacial outwash in the lower part of this soil profile in North Dakota, USA, is overlain by a layer of glacial till containing a random assortment of particles, ranging in size from small boulders to clays. Note the rounded edges of the rocks, evidence of the churning action within the glacier. Scale is marked every 10 cm.* (Photo courtesy of Ray R. Weil)

Glacial Outwash and Lacustrine Sediments. The torrents of water gushing forth from melting glaciers carried vast loads of sediment. In valleys and on plains where the glacial waters were able to flow away freely, the sediment formed an **outwash plain** (Figure 2.19). Such sediments, with sands and gravels sorted by flowing water, are common **valley fills**. Figure 2.19 shows the sorted layering of coarse and fine materials in glacial outwash overlaid by mixed materials of glacial till.

When the ice front came to a standstill, where there was no ready escape for the water, ponding began; ultimately, very large lakes were formed (Figure 2.19). The **lacustrine deposits** formed in these glacial lakes range from coarse delta materials and beach deposits near the shore to larger areas of fine silts and clay deposited from the deeper, more still waters at the center of the lake. Flat areas of inherently fertile (though not always well drained) soils developed from these materials as the lakes dried.

Parent Materials Transported by Wind

Wind is capable of picking up an enormous quantity of material at one site and depositing it at another. Wind can most effectively pick up material from soil or regolith that is loose, dry, and unprotected by vegetation. Dry, barren landscapes have served, and continue to serve, as sources of parent material for soils forming as far away as the opposite side of the globe. The smaller the particles, the higher and farther the wind will carry them. Wind-transported (**eolian**) materials important as parent material for soil formation include, from largest to smallest particle size: **dune sand**, **loess** (pronounced "luss"), and **aerosolic dust**. Windblown **volcanic ash** from erupting volcanoes is a special case that is also worthy of mention.

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Dune Sand. Along the beaches of the world's oceans and large lakes and over vast barren deserts, strong winds pick up medium and fine sand grains and pile them into hills of sand called *dunes*. The dunes, ranging up to 100 m in height, may continue to slowly shift their locations in response to the prevailing winds. Because most other minerals have been broken down and carried away by the waves, beach sand usually consists mainly of quartz, which is devoid of plant nutrients and highly resistant to weathering action. Nonetheless, over time dune grasses and other pioneering vegetation may take root, and soil formation may begin. In the United States, the sandy soils that extend for many kilometers east of Lake Michigan provide an example of this process. Some of the very deep sandy soils on the Atlantic coastal plain are thought to have formed on dunes marking the location of an ancient beach.

Desert sands, too, are usually dominated by quartz, but they may also include substantial amounts of other minerals that could contribute more to the establishment of vegetation and the formation of soils, should sufficient rainfall occur. The pure-white dunes of sand-sized gypsum at White Sands, New Mexico are a dramatic example of weatherable minerals in desert sands.

Loess. The windblown materials called *loess* are composed primarily of silt with some very fine sand and coarse clay. They cover wide areas in eastern Europe, Argentina, central China, and central United States (Figure 2.20*a*). Loess may be blown for hundreds of kilometers. The deposits farthest from the source are thinnest and consist of the finest particles.

In the United States (Figure 2.20*b*), the main sources of loess were the great barren expanses of till and outwash left in the Missouri and Mississippi river valleys by the retreating glaciers of the last Ice Age. During the winter months, winds picked up fine materials and moved them southward, covering the existing soils and parent materials with a blanket of loess that accumulated to as much as 8 m thick. Similar dust storms occur today as glaciers recede in Iceland, exposing barren outwash plains from which winds blow dust particles far out into the Atlantic Ocean. This input of mineral dust is thought to be an important source of iron for Ocean life.

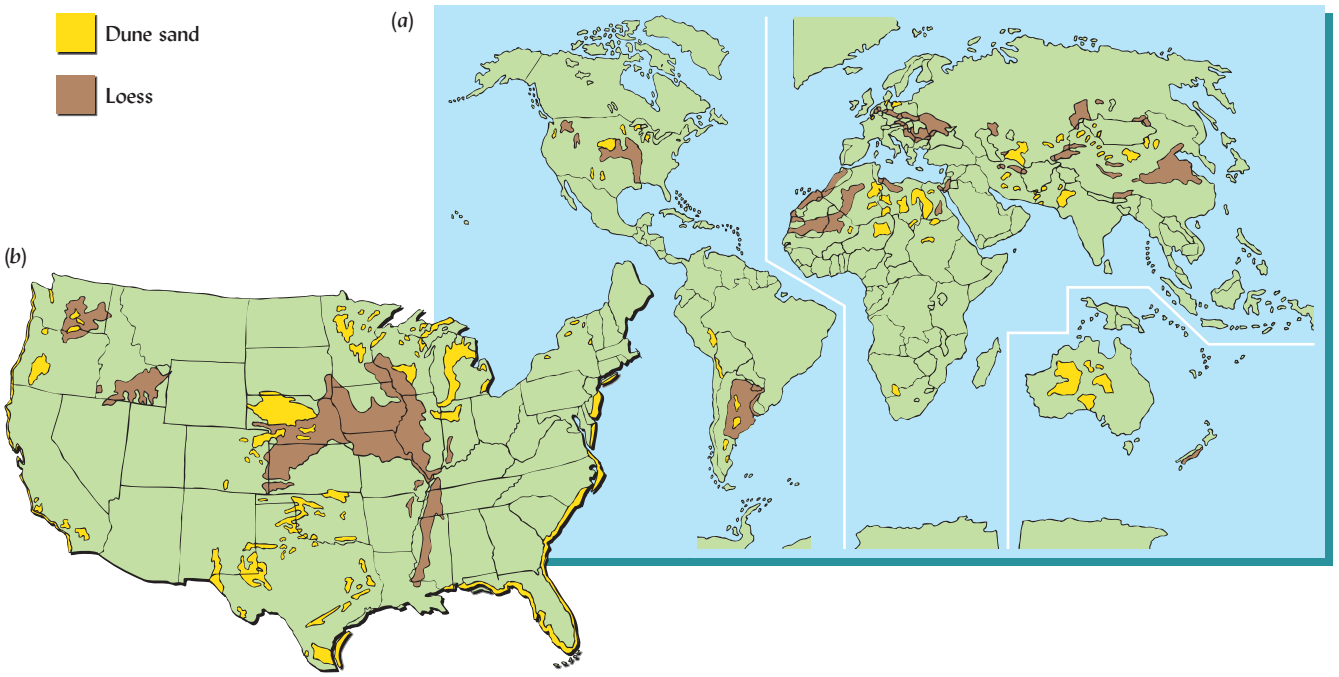

Figure 2.20 (a) *Major eolian deposits of the world include the loess deposits in Argentina, eastern Europe, northern China, and the large areas of dune sands in north Africa and Australia.* (b) *Approximate distribution of loess and dune sand in the United States. The soils that have developed from loess are generally silt loams, often quite high in fine sands. Note especially the extension of the central loess deposit down the eastern side of the Mississippi River and the smaller areas of loess in Washington, Oregon, and Idaho. The most prominent areas of dune sands are the Sand Hills of Nebraska and the dunes along the eastern shore of Lake Michigan.*

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In central and western China, loess deposits reaching 30–100 m in depth cover some 800,000 km^2. These materials have been windblown from the deserts of central Asia and are generally not associated directly with glaciers. These and other loess deposits tend to form silty soils of rather high fertility and potential productivity but also of high susceptibility to erosion by wind and water.

Aerosolic Dust. Very fine particles (about 1–10 μm diameter) are called *aerosolic dust* because they can remain suspended in air for thousands of kilometers before being deposited, usually with rainfall. Although this dust has not blanketed the receiving landscapes as thickly as is typical for loess, it does accumulate at rates that make significant contributions to soil formation. Much of the calcium carbonate in soils of the western United States probably originated as windblown dust. Recent studies have shown that dust, originating in the Sahara Desert of northern Africa and transported over the Atlantic Ocean in the upper atmosphere (Figure 2.21) is the source of much of the calcium and other nutrients found in the highly leached soils of the Amazon basin in South America. Likewise, in the springtime, dust from wind storms in the loess region of China blows across the Pacific Ocean to add soil parent materials (and air pollution) to the western part of North America.

Volcanic Ash. During volcanic eruptions, cinders fall in the immediate vicinity of the volcano, whereas fine, often glassy, ash particles may blanket extensive areas downwind. Soils developed from volcanic ash are most prominent within a few hundred kilometers of the volcanoes that ring the Pacific Ocean. Important areas of volcanic ash parent materials occur in Japan, Indonesia, New Zealand, Iceland, Mexico, Central America, Chile, and western United States. The soils formed are uniquely light and porous and tend to accumulate organic matter more rapidly than other soils in the area (Section 3.7). The volcanic ash tends to weather rapidly into allophane, a type of clay with unusual properties (see Section 8.5).

Organic Deposits

Organic material accumulates in wet places where plant growth exceeds the rate of residue decomposition. In such areas residues accumulate over the centuries from wetland plants such as

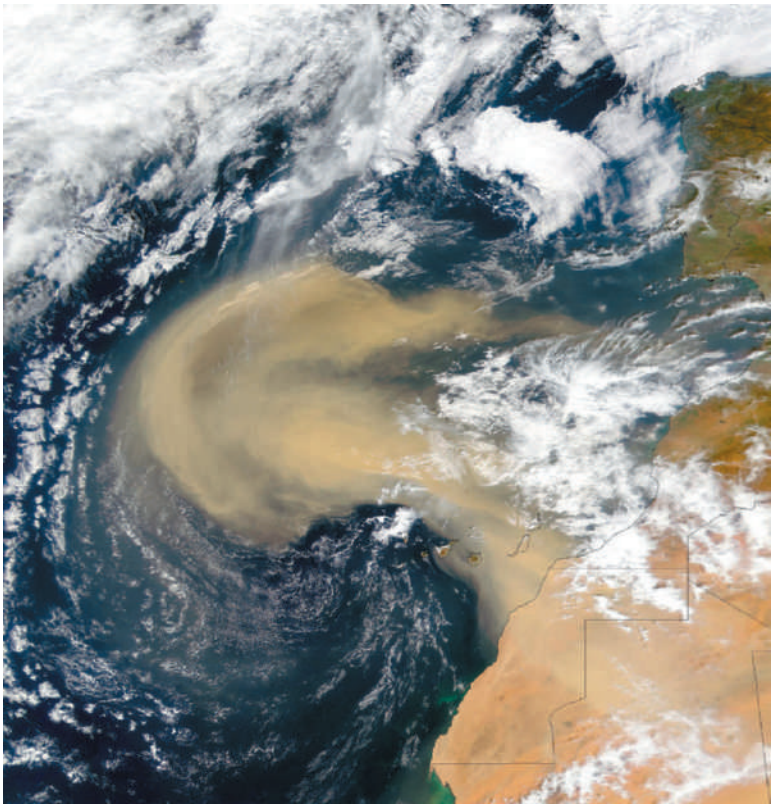

Figure 2.21 *A great cloud of dust from the Sahara desert in Africa rides the winds out into the Atlantic Ocean and up into Europe. Some of this dust also crosses the southern Atlantic Ocean and contributes to soils in South America. In a similar manner, giant dust clouds generated by wind erosion of loess soils in the Gobi desert region of China take about a week to ride the easterly winds across the Pacific Ocean before contributing to soil parent material (and air pollution) on the west coast of North America.* (Courtesy of NASA)

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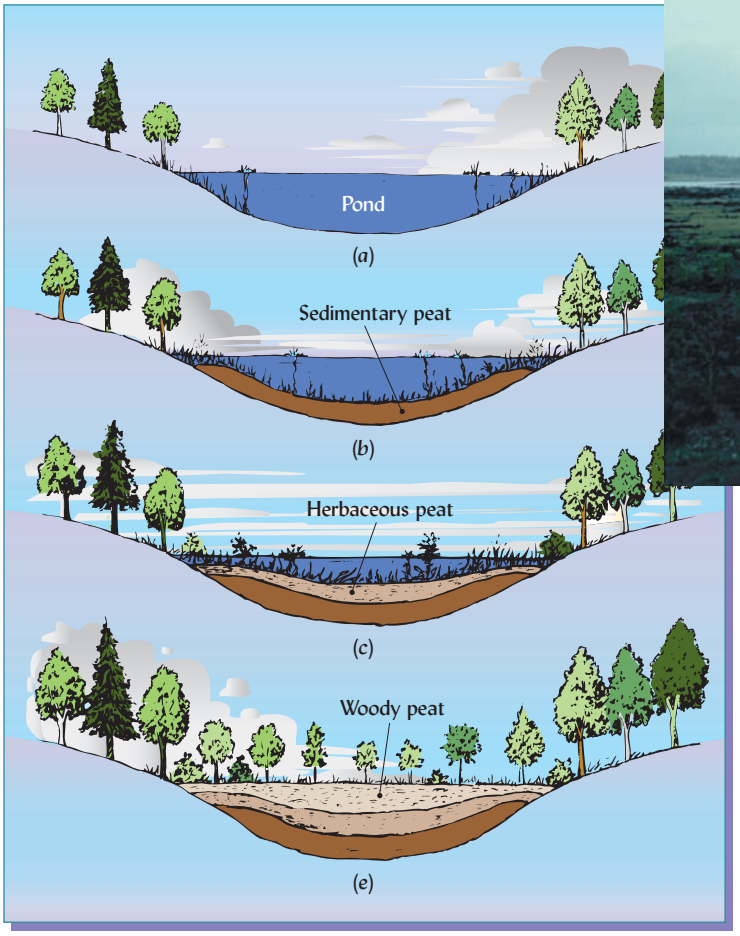

(d)

Figure 2.22 *Stages in the formation and use of a typical woody peat bog.* (a) *A pond, typically formed by glacial action, receives nutrients and sediments running off the surrounding uplands. These encourage aquatic plant growth, especially in the shallow water around the pond edges.* (b–d) *Organic debris fills the bottom of the pond as increasingly rooted, emergent vegetation invades.* (e) *Eventually shrubs and trees take root in the peat and cover the area. Many such bogs have been cleared of trees and drained by ditches to remove some of the water, exposing an organic muck soil that is often highly productive for vegetable crops. The bog in the photo is in central Michigan, USA.* (Photo courtesy of Ray R. Weil)

pondweeds, cattails, sedges, reeds, mosses, shrubs, and certain trees. These residues sink into the water, where their decomposition is limited by lack of oxygen. As a result, organic deposits often accumulate up to several meters in depth (Figure 2.22). Collectively, these organic deposits are called **peat**.

Distribution and Accumulation of Peats. Peat deposits are found all over the world, but most extensively in the cool climates and in areas that have been glaciated. About 75% of the 340 million hectares of peat lands in the world are found in Canada and northern Russia.

The rate of peat accumulation varies from one area to another, depending on the balance between production of plant material and its loss by decomposition. Cool climates and acidic conditions favor slow decomposition but also slower plant production. Warm climates and alkaline conditions favor rapid losses but also rapid plant production. Enrichment with nutrients may increase the rate of organic production more than it does the rate of decomposition, leading to very high net accumulation rates (Table 2.4). As we shall see in Chapter 12, artificial drainage, used to remove excess water from a peat soil, lets air into the peat and drastically alters the balance between production and decomposition of organic matter, causing a reversal of the accumulation process and a loss or subsidence of the peat soil.

Types of Peat Materials. Based on the nature of the parent materials, four kinds of peat are recognized:

1. Moss peat, the remains of mosses such as sphagnum
2. Herbaceous peat, residues of herbaceous plants such as sedges, reeds, and cattails
3. Woody peat, from the remains of woody plants, including trees and shrubs
4. Sedimentary peat, remains of aquatic plants (e.g., algae) and of fecal material of aquatic animals

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Table 2.4
VARIOUS FRESHWATER WETLANDS, THEIR RATES OF ACCRETION (INCREASING SOIL THICKNESS), AND ACCUMULATION OF CARBON, NITROGEN, AND PHOSPHOROUS IN THEIR PEAT SOILS

			Accumulation Rate, $g/m^2/yr$		
Type and Location of Wetland	Characteristics of Wetland Types	Accretion Rate, mm/yr	C	N	P
Bogs (Massachusetts, USA)	**Bogs** are peat-accumulating ponds with no outflow and little inflow. They receive little calcium from the surrounding landscape and are therefore quite acidic.	4.3	90	1.2	—
Fens (Michigan, USA)	**Fens** are peat-accumulating ponds with no outflow and little inflow. Calcium-rich mineral matter from the surrounding landscapes makes them relatively alkaline.	0.9	42	3.0	0.11
Pocosin swamps (North Carolina, USA)	**Swamps** are periodically inundated with shallow, slow-moving water and dominated by shrubs and trees.	2.6	127	3.0	0.06
Okefenokee swamp (Georgia, USA)		—	82	3.8	0.15
Everglades marsh (Florida, USA), unenriched	**Marshes** are periodically inundated with shallow, slow-moving water and dominated by grasses and herbaceous plants. The Everglades is a very large wetland	1.4	65	4.7	0.06
Everglades marsh (Florida, USA), enriched	Area in Florida with both marshy and swampy components.	6.7	223	16.6	0.46

(Data compiled by Craft and Richardson [1998])

Organic deposits generally contain two or more of these kinds of peats, either in alternating layers or as mixtures. Because the succession of plants, as the residues accumulate, tends to favor trees (see Figure 2.22), woody peats often dominate the surface layers of organic materials.

In cases where a wetland area has been drained, woody peats tend to make very productive agricultural soils that are especially well suited for vegetable production. While moss peats have high water-holding capacities, they tend to be quite acidic. Sedimentary peat is generally undesirable as an agricultural soil. This material is highly colloidal and compact and is rubbery when wet. Upon drying, it resists rewetting and remains in a hard, lumpy condition. Fortunately, it occurs mostly deep in the profile and is unnoticed unless it interferes with drainage of the bog area.

The organic material is called **peat**, or **fibric**, if the residues are sufficiently intact to permit the plant fibers to be identified. If most of the material has decomposed sufficiently so that little fiber remains, the term **muck** or **sapric** is used. In mucky peats (**hemic** materials) only some of the plant fibers can be recognized.

Wetland Preservation. Wetland areas are important environmental buffers and natural habitats for wildlife. Drainage of these areas reduces the benefits of wetlands. While organic soils are the foundation for some very productive agricultural systems, environmentalists argue that such use is unsustainable because, once drained, the organic deposits will decompose and disappear after a century or so; therefore, these areas might be better left in (or returned to) their natural state (see Section 7.7).

Recognizing that the effects of **parent materials** on soil properties are modified by the combined influences of **climate**, **biotic activities**, **topography**, and **time**; we will now turn to these other four factors of soil formation, starting with climate.

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2.4 HOW DOES CLIMATE AFFECT SOIL FORMATION?

Climate is perhaps the most influential of the four factors acting on parent material because it determines the nature and intensity of the weathering that occurs over large geographic areas. The principal climatic variables influencing soil formation are ***effective precipitation*** (see Box 2.1) and *temperature*, both of which affect the rates of chemical, physical, and biological processes.

BOX 2.1
EFFECTIVE PRECIPITATION FOR SOIL FORMATION

Water from rain and melting snow is a primary requisite for parent material weathering and soil development. To fully promote soil development, water must not only enter the profile and participate in weathering reactions, but also percolate through the profile and translocate soluble weathering products.

Let's consider a site that receives an average of 600 mm of rainfall per year. The amount of water leaching through a soil is determined not only by the total annual precipitation but also by at least four other factors as well (Figure 2.23).

a. **Seasonal distribution** of precipitation. The 600 mm of rainfall distributed evenly throughout the year, with about 50 mm each month, is likely to cause less soil leaching or erosion than the same annual amount of rain falling at the rate of 100 mm per month during a 6-month rainy season.

b. **Temperature and evaporation**. In a hot climate, evaporation from soils and vegetation is much higher than in a cool climate. Therefore, in the hot climate, much less of the 600 mm will be available for percolation and leaching. Most or all will evaporate soon after it falls on the land. Thus, 600 mm of rain may cause more leaching and profile development in a cool climate than in a warmer one. Similar reasoning would suggest that rainfall concentrated during

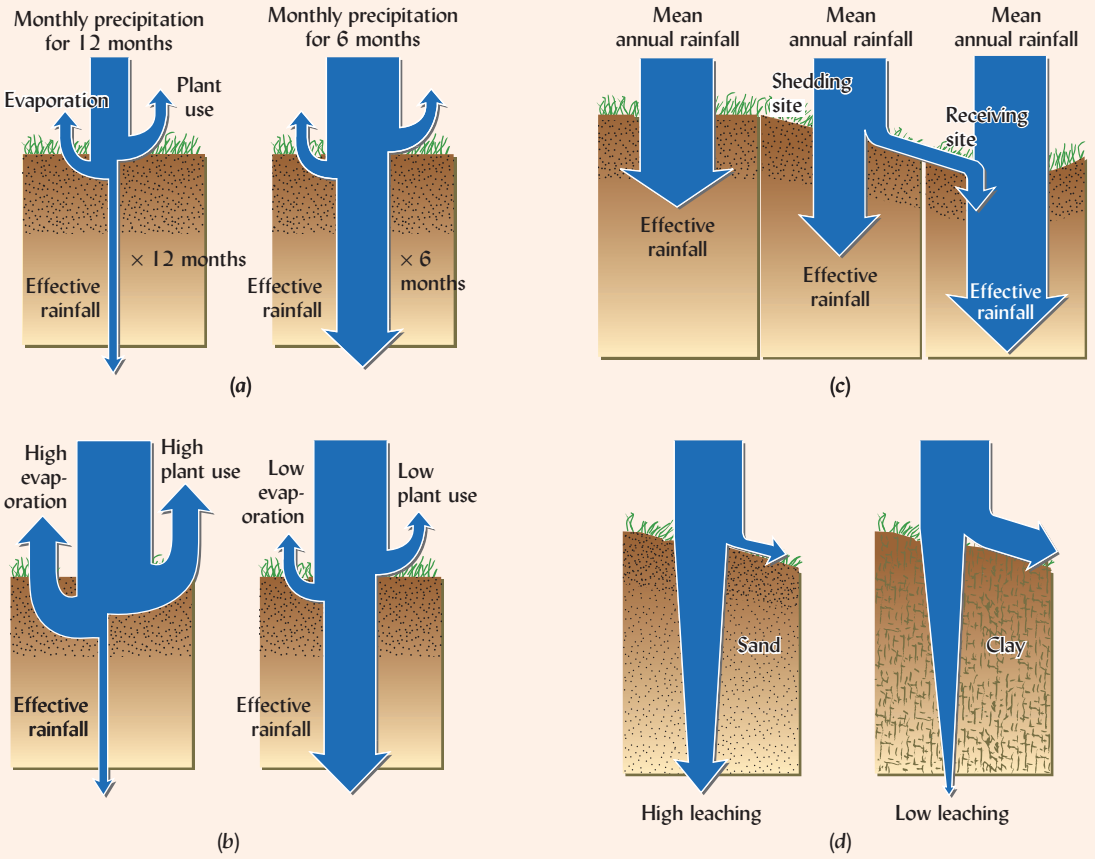

Figure 2.23 *The seasonal rainfall distribution* (a), *evaporative demand* (b), *site topography* (c), *and soil permeability* (d) *interact to determine how effectively precipitation can influence soil formation.*
(Diagram courtesy of Ray R. Weil)

(continued)

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BOX 2.1

EFFECTIVE PRECIPITATION FOR SOIL FORMATION *(CONTINUED)*

a mild winter (as in California, USA) may be more effective in leaching the soil than the same amount of rain concentrated in a hot summer (as in the Great Plains, USA).

c. **Topography**. Water falling on a steep slope will run downhill so rapidly that only a small portion will enter the soil where it falls. Therefore, even though they receive the same rainfall, level or concave sites will experience more percolation and leaching than steeply sloping sites. The effective rainfall can be said to be greater on the level site than on the sloping one. The concave site will receive the greatest effective rainfall because, in addition to direct rainfall, it will collect the runoff from the adjacent sloping site.

d. **Permeability**. Even if the above conditions are the same, more rainwater will infiltrate and leach through a coarse, sandy profile than a tight, clayey one. Therefore the sandy profile can be said to experience a greater effective precipitation, and more rapid soil development may be expected.

Effective Precipitation

We have already seen that water is essential for all the major chemical weathering reactions. To be effective in soil formation, water must penetrate into the regolith. The greater the depth of water penetration, the greater the depth of weathering soil and development. Surplus water percolating through the soil profile transports soluble and suspended materials from the upper to the lower layers. It may also carry away soluble materials in the drainage waters. Thus, percolating water stimulates weathering reactions and helps differentiate soil horizons.

Likewise, a deficiency of water is a major factor in determining the characteristics of soils of dry regions. Soluble salts are not leached from these soils, and in some cases they build up to levels that curtail plant growth. Soil profiles in arid and semiarid regions are also apt to accumulate carbonates and certain types of cracking clays.

Temperature

For every 10 °C rise in temperature, the rates of biochemical reactions more than double. Temperature and moisture both influence the organic matter content of soil through their effects on the balance between plant growth and microbial decomposition (see Figure 12.27). If warm temperatures and abundant water are present in the profile at the same time, the processes of weathering, leaching, and plant growth will be maximized. The very modest profile development characteristic of cold areas contrasts sharply with the deeply weathered profiles of the humid tropics (Figures 2.24 and 2.11).

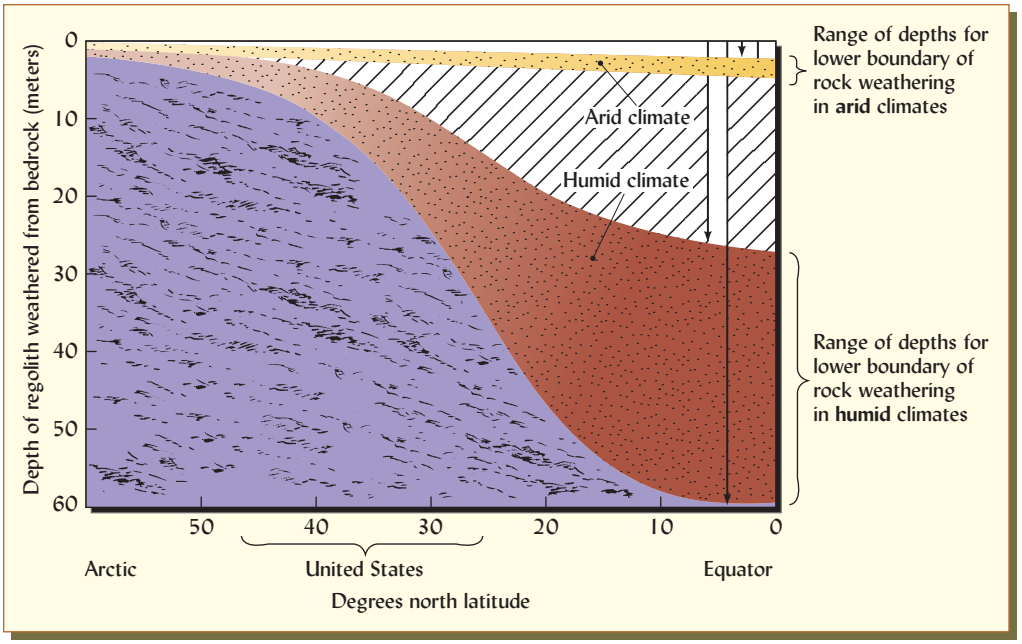

Figure 2.24 *A generalized illustration of the effects of two climatic variables, temperature and precipitation, on the depths of regolith weathered in bedrock. The stippled areas represent the range of depths to which the regolith typically extends. In cold climates (arctic regions), the regolith is shallow under both humid and arid conditions. In the warmer climates of the lower latitudes, the depth of the residual regolith increases sharply in humid regions but is little affected in arid regions. Under humid tropical conditions, the regolith may be 50 or more meters in depth. The vertical arrows represent depths of weathering near the Equator. Remember that soil depth may not be as great as regolith depth.* (Diagram courtesy of N. C. Brady)

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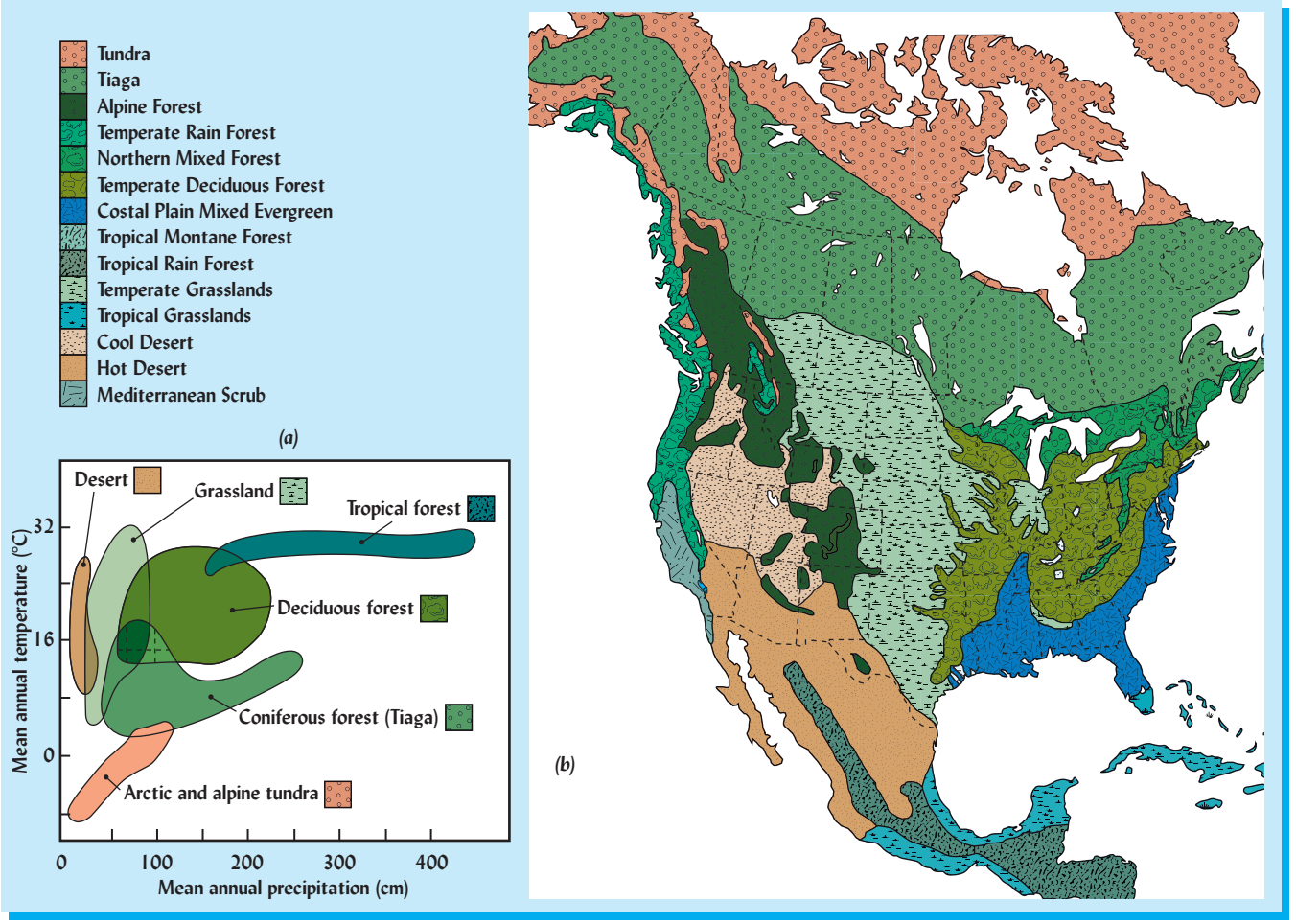

Figure 2.25 *Effect of climate on vegetation.* (a) *General distribution of vegetation ecotypes (biomes) along gradients of mean annual temperature and precipitation.* (b) *Major biomes in North America.* [(a) from National Science Foundation (NSF) (1975); (b) from U.S. Department of Energy, Oak Ridge Lab]

Considering soils with similar temperature regime, parent material, topography, and age, increasing effective annual precipitation generally leads to increasing clay and organic matter contents, greater acidity, and lower ratio of Si/Al (an indication of more highly weathered minerals; see Table 2.3). However, many places have experienced climates in past geologic epochs that were very different from the climate evident today. This fact is illustrated in certain old landscapes in arid regions, where highly leached and weathered soils stand as relics of the humid tropical climate that prevailed there many thousands of years ago. Climate also influences the natural vegetation. Humid climates favor the growth of trees (Figure 2.25). In contrast, grasses are the dominant native vegetation in subhumid and semiarid regions, while shrubs and brush of various kinds dominate in arid areas. Thus, climate exerts its influence partly through the soil-forming factor we will consider next: living organisms.

2.5 HOW DO LIVING ORGANISMS (INCLUDING PEOPLE) AFFECT SOIL FORMATION?

Organic matter accumulation, biochemical weathering, profile mixing, nutrient cycling, and aggregate stability are all enhanced by the activities of organisms in the soil. Vegetative cover reduces natural soil erosion rates, thereby slowing down the rate of mineral surface soil removal. Organic acids produced from certain types of plant leaf litter bring iron and aluminum into solution by complexation and accelerate the downward movement of these metals and their accumulation in the B horizon.

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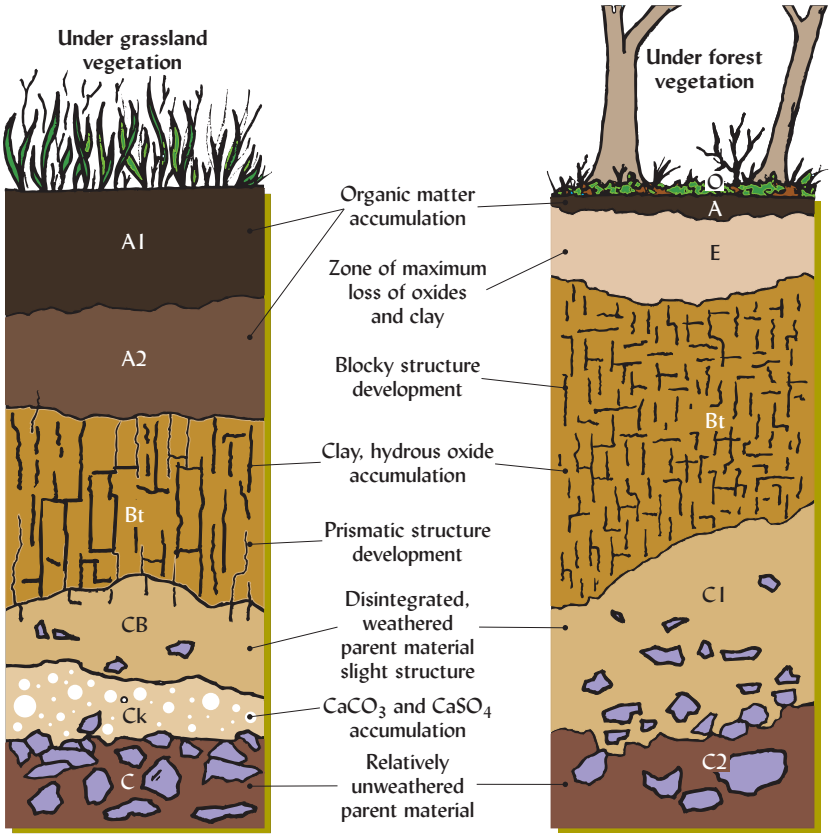

Figure 2.26 *Natural vegetation influences the type of soil eventually formed from a given parent material (calcareous till, in this example). The grassland vegetation is likely to occur in a somewhat less humid climate than the deciduous forest. The amount, and especially the vertical distribution, of organic matter that accumulates in the upper part of the profile differs markedly between the vegetation types. The forested soil exhibits surface layers (O horizons) of leaves and twigs in various stages of decomposition, along with a thin mineral A horizon, into which some of the surface litter has been mixed. In contrast, most of the organic matter in the grassland is added as fine roots distributed throughout the upper 1 m or so, creating a thick mineral A horizon. Also note that calcium carbonate has been solubilized and has moved down to the lower horizons (Ck) in the grassland soils, while it has been completely removed from the profile in the more acidic, leached forested soil. Under both types of vegetation, clay and iron oxides move downward from the A horizon and accumulate in the B horizon, encouraging the formation of characteristic soil structure. In the forested soil, the zone above the B horizon usually becomes a distinctly bleached E horizon, partly because most of the organic matter is restricted to the near-surface layers, and partly because decomposition of the forest litter generates organic acids that remove the brownish iron oxide coatings. Compare these mature profiles to the changes over time discussed in Sections 2.7 and 2.8.*
(Diagrams courtesy of Ray R. Weil)

Role of Natural Vegetation

Organic Matter Accumulation. The effect of vegetation on soil formation can be seen by comparing properties of soils formed under grassland and forest vegetation near the boundary between these two ecosystems (Figure 2.26). In the grassland, much of the organic matter added to the soil is from the deep, fibrous, root systems. By contrast, tree leaves falling on the forest floor are a principal source of soil organic matter in the forest. Another difference is the frequent occurrence in grasslands of fires that destroy large amounts of aboveground biomass and create bits of charcoal that accumulate in the soil. Also, the extreme acidity under certain forests inhibits such soil organisms as earthworms that otherwise would mix much of the surface litter into the mineral soil. As a result, the soils under grasslands generally develop a thicker A horizon with a deeper distribution of organic matter than in soils under nearby forests, which characteristically store most of their organic matter in the forest floor (O horizons) and a thin A horizon. The microbial community in a typical grassland soil is dominated by bacteria, while that of the forest soil is dominated by fungi (see Chapter 11 for details). Differences in microbial action affect the aggregation of the mineral particles into stable granules and the rate of nutrient cycling. The light-colored, leached E horizon typically found under the O or A horizon of a forested soil results from the action of organic acids generated mainly by fungi in the acidic forest litter. An E horizon is generally not found in a grassland soil.

Cation Cycling by Trees.[6] The ability of natural vegetation to accelerate the release of nutrient elements from minerals by biogeochemical weathering, and to take up these elements from the soil, strongly influences the characteristics of the soils that develop. Soil acidity is especially affected. Differences occur not only between grassland and forest vegetation but also between different species of forest trees. Litter falling from coniferous trees (e.g., pines, firs, spruces, and hemlocks) will recycle only a small amount of calcium, magnesium, and

[6]For a book with intriguing papers on the ecological impacts and competing theories of how trees affect nutrient cycling and soil formation, see Binkley and Menyailo (2005).

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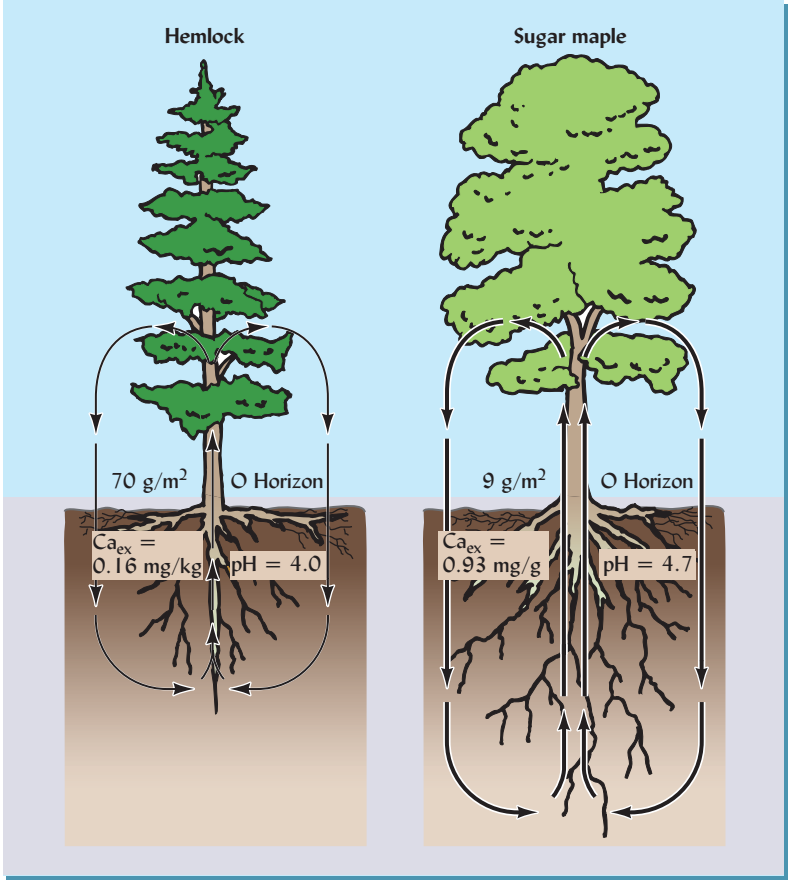

Figure 2.27 *Nutrient cycling is an important process by which plants affect the soil in which they grow, altering the course of soil development and the suitability of the soil environment for future generations of vegetation. For example, hemlock (a conifer) and sugar maple (a deciduous hardwood) differ markedly in their ability to accelerate mineral weathering, mobilize nutrient cations, and recycle them to the upper soil horizons. Sugar maple roots are efficient at taking up Ca from soil minerals, and the maple leaves produced contain high concentrations of Ca. When these leaves fall to the ground, they decompose rapidly and release large amounts of Ca^{2+} ions that become adsorbed as exchangeable Ca^{2+} on humus and clay in the O and A horizons. This influx of Ca^{2+} ions may somewhat retard acidification of the surface layers. However, the maple roots' efficient extraction of Ca from minerals in the parent material may accelerate acidification and weathering in deeper soil horizons. In contrast, hemlock needles are Ca-poor, much slower to decompose, and therefore result in a thicker O horizon, greater acidity in the O and upper mineral horizons, but possibly less rapid weathering of minerals in the underlying parent material.* [Data for a Connecticut forest reported by Van Breemen and Finzi (1998)]

potassium compared to that recycled by litter from some deciduous trees (e.g., yellow poplar, beech, oaks, and maples), which take up and store much larger amounts of these cations (Figure 2.27). Conifer tree roots take up less Ca, Mg, and K from minerals weathering deep in the profile and allow more of these nonacidic cations to be lost by leaching. Therefore, soil acidity often develops more strongly in the surface horizons under coniferous vegetation than under most deciduous trees. Furthermore, the acidic, resinous needles from conifer trees resist decomposition and discourage earthworm populations leading to the accumulation of a thick O horizon with distinctly separate layers of fibric (undecomposed) and sapric (highly decomposed) material. The leaves of deciduous trees generally break down more readily and form a thinner forest floor with less distinction between layers and with more litter mixed into the A horizon. In Chapter 8 (Box 8.2) we will see that nutrient cycling by plant roots can even alter the types of clay minerals found in a soil.

Heterogeneity in Rangelands. In arid and semiarid rangelands, competition for limited soil water does not permit vegetation dense enough to completely cover the soil surface. Scattered shrubs or bunch grasses are interspersed with openings in the plant canopy where the soil is bare or partially covered with plant litter. The widely scattered vegetation alters soil properties in several ways. Plant canopies trap windblown dust that is often relatively rich in silt and clay. Roots scavenge nutrients such as nitrogen, phosphorus, potassium, and sulfur from the interplant areas. These nutrients are then deposited with the leaf litter under the plant canopies. The decaying litter adds organic acids, which lower the soil pH and stimulate mineral weathering. As time goes on, the relatively bare soil areas between plants decline in fertility and may increase in size as they become impoverished and even less inviting for the establishment of plants. Simultaneously, the vegetation creates "islands" of enhanced fertility, thicker A horizons, and often more deeply leached calcium carbonate (see Figure 2.28 and Section 10.1).

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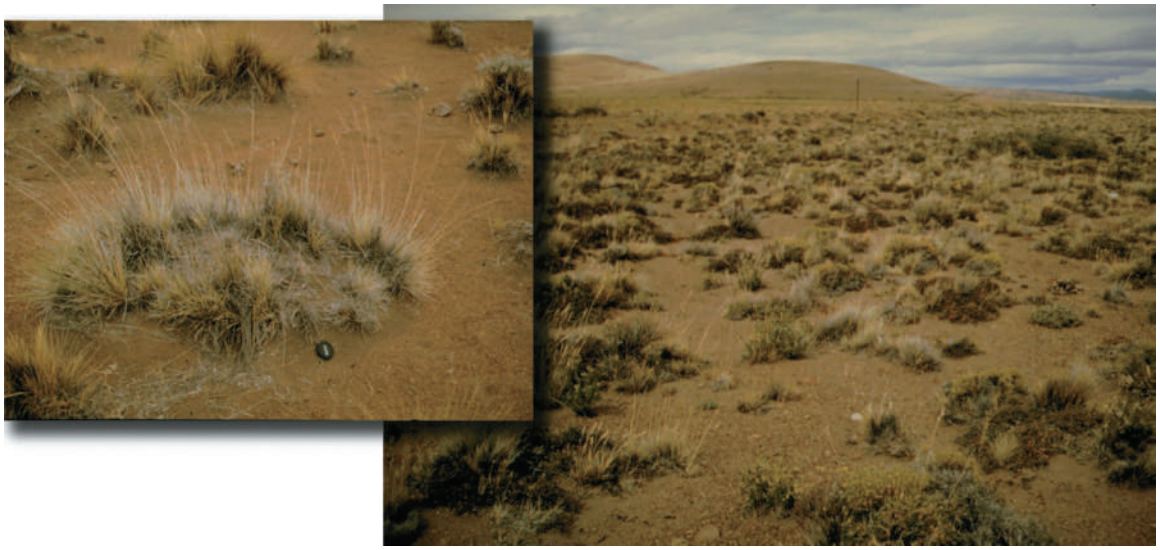

Figure 2.28 *The scattered bunch grasses of this semiarid rangeland in the Patagonia region of Argentina have created "islands" of soil with enhanced fertility and thicker A horizons. A lens cap placed at the edge of one of these islands provides scale and highlights the increased soil thickness under the plant canopy. Such small-scale soil heterogeneity associated with plants is common where soil water limitations prevent complete plant ground cover.* (Photos courtesy of Dr. Ingrid Burke, Haub School of Environment and Natural Resources, University of Wyoming)

Role of Animals

Animals can have far-reaching and often rapid impacts on the course of soil formation. Large animals such as gophers, moles, and prairie dogs bore into the lower soil horizons, bringing materials to the surface. Their tunnels are often open to the surface, encouraging movement of water and air into the subsurface layers. In localized areas, they enhance mixing of the lower and upper horizons by creating, and later refilling, underground tunnels. For example, dense populations of prairie dogs may completely turn over the upper meter of soil in the course of several thousand years. Old animal burrows in the lower horizons often become filled with soil material from the overlying A horizon, creating profile features known as *crotovinas* (Figure 2.29). In certain situations, animal activity may arrest soil development by accelerating soil erosion. Such activity in alpine meadows is illustrated in Figure 2.30.

Invertebrate Animals. Earthworms, ants, and termites mix the soil as they burrow, significantly affecting soil formation. Earthworms ingest soil particles and organic residues, enhancing the availability of plant nutrients in the material that passes through their bodies. They aerate and stir the soil and enhance soil aggregation. Ants and termites, as they build mounds, also transport soil materials from one horizon to another. In general, the mixing activities of animals, sometimes called **pedoturbation**, tend to undo or counteract the tendency of other soil-forming processes to accentuate the differences among soil horizons. Termites and ants may also retard soil profile development by denuding large areas of soil around their nests, leading to increased loss of soil by erosion (Figure 2.31). On the other hand, the burrows constructed by ants, termites, and earthworms may significantly increase the amount of water that enters and moves through the soil (see Sections 6.5 and 10.1), thus stimulating biological productivity, weathering, and soil formation.

Human Influences and Urban Soils. Human activities widely influence soil formation. For example, in Africa about 3000 years ago, Bantu-speaking farmers using fire to clear forest land for shifting cultivation (see Section 20.7) facilitated the abrupt change in the vegetation of central Africa from dense rain forest to a more open tree-scattered grassland (savanna). The sediments that washed off the land into the Atlantic Ocean at that time left evidence of intensified biogeochemcial

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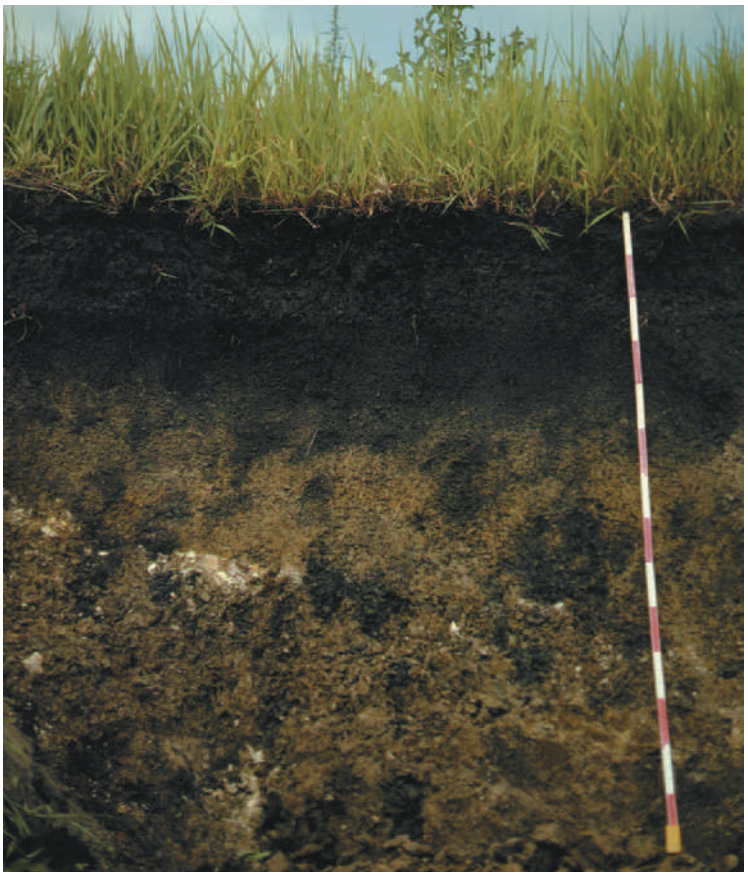

Figure 2.29 *Abandoned animal burrows in one horizon filled with soil material from another horizon are called* crotovinas. *In this Illinois prairie soil, dark, organic-matter-rich material from the A horizon has filled in old prairie dog burrows that extend into the B horizon. The dark circular shapes in the subsoil mark where the pit excavation cut through these burrows. Scale marked every 10 cm.* (Photo courtesy of Ray R. Weil)

Figure 2.30 *Pedoturbation by pocket gophers (family* Geomyidae*) can accelerate erosion and inhibit soil profile development in alpine tundra landscapes. In the winter the gophers make tunnels through the thick snow as they move about on the soil surface feeding on aboveground vegetation. Later, as they burrow through the soil, they pack these snow tunnels with excavated soil material. When the snow melts, the tubular cylinders of packed soil remain as snow casts like those shown in these scenes from two areas in the Rocky Mountains in the United States. The fine soil in the snow casts and that disturbed by the burrowing are highly susceptible to erosion by rain and snowmelt water. The gopher-disturbed area is thought to erode 10–100 times faster than comparable undisturbed tundra. See also Black et al. (1994) and Thorn (1978).* (Large photo courtesy Robert Darmody, University of Illinois; inset photo courtesy of Ray R. Weil)

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Figure 2.31 *How ants may influence profile development.* (Left) *Vertical mixing by bringing up from the C horizon bits of weathered granite rock the size of coarse sand (termed* grus*) in an eastern Colorado prairie (11 cm knife handle) in the United States.* (Right) *Removal of vegetation from around another ant nest in formerly irrigated land in the Nevada desert in the United States leaves the soil unprotected and subject to crusting and erosion (clearing is 9 m across).* (Photos courtesy of Ray R. Weil)

weathering rates resulting from the loss of forest canopy on a wide scale. Similarly, it is believed that during the last few thousand years Native Americans regularly set fires to maintain large areas of prairie grasslands in Indiana and Michigan. In more recent times, human destruction of natural vegetation (trees and grass) and subsequent tillage of the soil for crop production have abruptly modified soil formation. Likewise, irrigating an arid region soil drastically influences the soil-forming factors, as does adding fertilizer and lime to soils of low fertility. In surface mining and urbanizing areas today, bulldozers may have an effect on soils almost akin to that of the ancient glaciers; they level and mix soil horizons and set the clock of soil formation back to zero.

In other situations, people actually engineer new soils, such as those used in most golf greens and certain athletic fields (see Section 5.6), the cover material used to vegetate and seal completed landfills (see Section 18.9), and the plant media on rooftop gardens. Humans may even reverse the processes of erosion and sedimentation that normally destroy soils and counteracts soil formation (see Section 2.6 and Chapter 17). For example, sediments dredged from the bottom of the bays and rivers can be placed as a thick layer of muddy parent material on land—commonly on barren, highly disturbed land. Within a year, the new parent material will dry out, oxidize, begin to develop such soil characteristics as granular and prismatic structure (Figure 2.32). It will soon support increasingly lush vegetation, which in turn will facilitate organic matter accumulation and further soil development.

Human impacts on soils are widespread and their potential must be considered in understanding the roles of soils in most landscapes. In urban areas the human influence is pervasive and special consideration will be given to soils in these environments (Section 2.10).

2.6 HOW DOES TOPOGRAPHY AFFECT SOIL FORMATION?

Topography relates to the configuration of the land surface and is described in terms of differences in elevation, slope, and landscape position—in other words, the lay of the land. The topographical setting may either hasten or retard the work of climatic forces (as shown in Box 2.1). Steep slopes generally encourage rapid soil loss by erosion and allow less rainfall to enter the soil before running off. In semiarid regions, the lower effective rainfall on steeper slopes also results in less complete vegetative cover, so there is less plant contribution to soil formation. For all of these reasons, steep slopes prevent the formation of soil from getting very far ahead of soil destruction. Therefore, soils on steep terrain tend to have rather shallow, poorly developed profiles in comparison to soils on nearby, more level sites (Figure 2.33).

In swales and depressions that collect runoff water, the regolith is usually more deeply weathered and soil profile development is more advanced. However, in the lowest landscape positions, water may saturate the regolith to such a degree that drainage and aeration are

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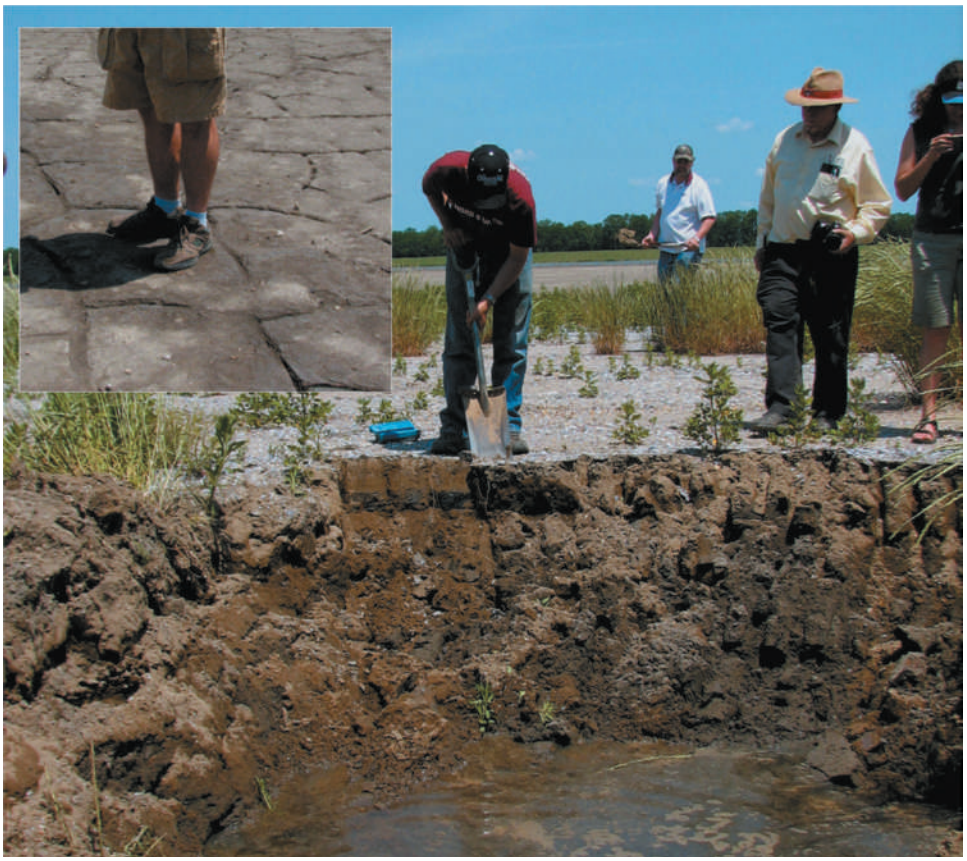

Figure 2.32 *Soil formation taking place in sediments dredged from the bottom of the Potomac River at Washington, DC in the United States. The "dredge spoil" was barged several hundred kilometers to a farm in Virginia where the sediments were spread several meters thick on land previously made barren by mining activities. Note the cracks forming during the first year after deposition as the soupy material drains and dries (inset). Within three years, the reduced black begins to oxidize and turn brown in color and cracks begin to define soil structural peds, including large incipient prisms. The water table level can be seen as the level of water in the excavated soil observation pit. Within just a few years, the upper 50 cm of material had oxidized and formed soil structure such that good crops could be grown on the young soil. A key factor in the rapid formation of a productive agricultural soil by this human activity was fact that the sediments came from a freshwater (non-brackish) river near a nonindustrial city and therefore the dredge spoil was initially non-contaminated, non-salty, and low in sulfides. Salty, sulfide-rich marine sediments would have produced a much more problematic soil (see Sections 9.6 and 10.6)* [For more information see Daniels et al. (2007). Photos courtesy of Ray R. Weil]

restricted. Here the weathering of some minerals and the decomposition of organic matter are retarded, whereas the loss of iron and manganese is accelerated. In such low-lying topography, special profile features characteristic of wetland soils may develop (see Section 7.7 on the soils of wetlands).

Soils that commonly occur together in the landscape in sequence are termed a **catena** (from the Latin meaning *chain*—visualize a length of chain suspended from two adjacent hills with each link in the chain representing a soil). Each member of the catena occupies a characteristic topographic position. Soils in a catena generally exhibit properties that reflect the

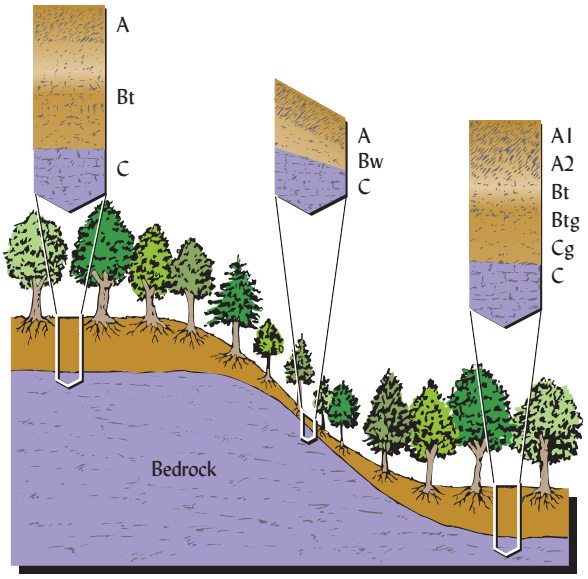

Figure 2.33 *Topography influences soil properties, including soil depth. The diagram on the left shows the effect of slope on the profile characteristics and the depth of a soil on which forest trees are the natural vegetation. The photo on the right illustrates the same principle under grassland vegetation. Often a relatively small change in slope can have a great effect on soil development. See Section 2.9 for explanation of horizon symbols.* (Photo courtesy of Ray R. Weil)

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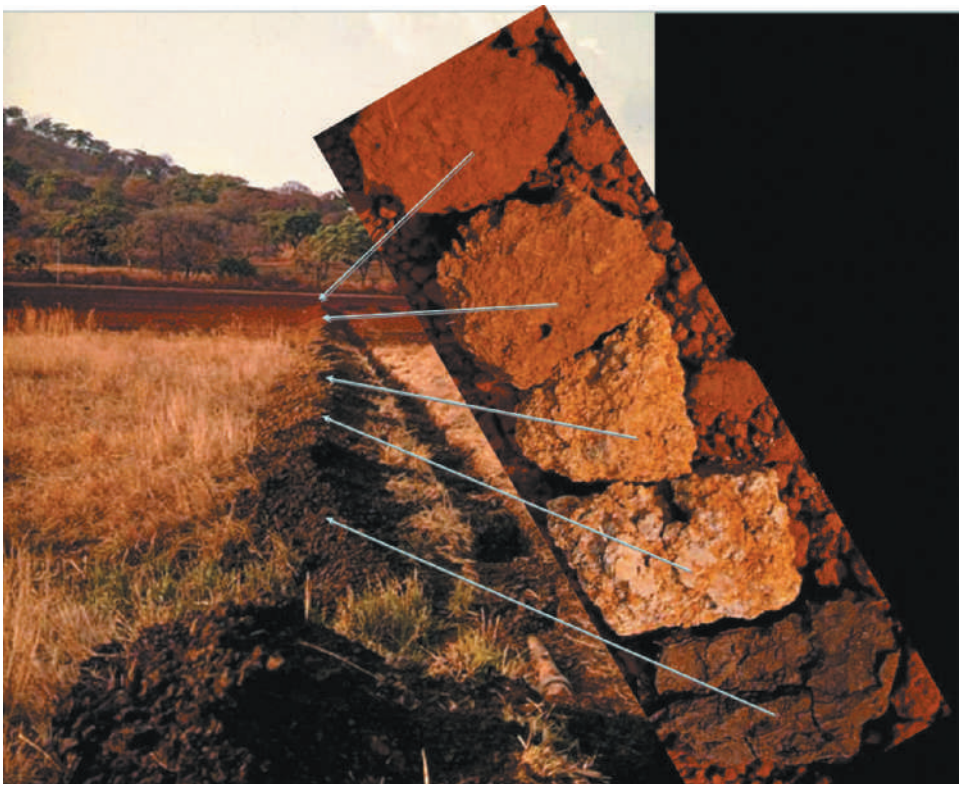

Figure 2.34 *A soil catena or toposequence in central Zimbabwe. Redder colors indicate better internal drainage. A ditch has been excavated going up the slope, exposing the colors of the B horizons. Inset: B-horizon clods from each soil in the catena.* (Photos courtesy of Ray R. Weil)

influence of topography on water movement and drainage (see, e.g., Figure 2.23*c*). A **toposequence** is a type of catena, in which the differences among the soils result almost entirely from the influence of topography because the soils in the sequence all share the same parent material and have similar conditions regarding climate, vegetation, and time (see, e.g., Figures 2.33 and 2.34).

Interaction with Vegetation. Topography often interacts with vegetation to influence soil formation. In grassland–forest transition zones, trees are commonly confined to depressions where soil is generally wetter than in upland positions. As would be expected, soil in the depressions is quite different from that in the uplands. The influence of climate in regulating soil development will be much reduced in landscape depressions where water stands for part or all of the year. Some low-lying areas may give rise to peat bogs and, in turn, to organic soils (see Figure 2.22).

Slope Aspect. Topography affects the absorbance of solar energy in a given landscape. In the northern hemisphere, south-facing slopes are more perpendicular to the sun's rays and are generally warmer and thereby commonly lower in moisture than their north-facing counterparts (see also Figure 7.35). Consequently, soils on the south slopes tend to be lower in organic matter and are not so deeply weathered.

Salt Buildup. In arid and semiarid regions, topography influences the buildup of soluble salts. Dissolved salts from surrounding upland soils move on the surface and through the underground water table to the lower-lying areas (see Section 10.3). There they rise to the soil surface as the water evaporates, often accumulating to plant-toxic levels.

Parent Material Interactions. Topography can also interact with parent material. For example, in areas of tilted beds of sedimentary rock, the ridges often consist of resistant sandstone, whereas the valleys are underlaid by more weatherable limestone. In many landscapes, topography reflects the distribution of residual, colluvial, and alluvial parent materials, with residual materials on the upper slopes, colluvium covering the lower slopes, and alluvium filling the valley bottom (Figure 2.35).

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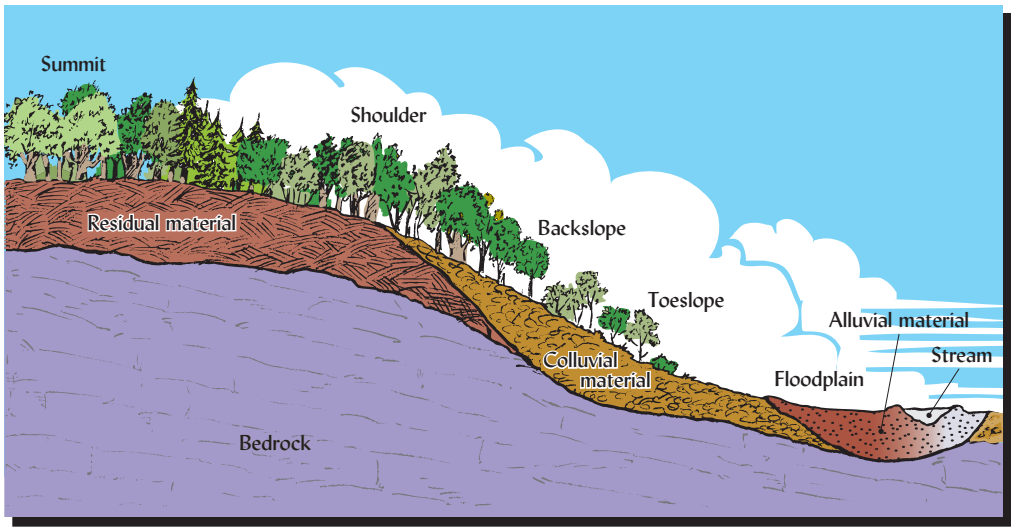

Figure 2.35 *An interaction of topography and parent material as factors of soil formation. The soils on the summit, toeslope, and floodplain in this idealized landscape have formed from residual, colluvial, and alluvial parent materials, respectively.*
(Diagram courtesy of Ray R. Weil)

2.7 HOW DOES TIME AFFECT SOIL FORMATION?[7]

Soil-forming processes take time to show their effects. The weathering of rock generally creates only 0.01–0.1 mm of new soil material per year, the rate of soil formation depending on the environmental factors just discussed. However, the rates of rock weathering into soil material tend to be greatest for the thinnest soils on steep slopes and rates as high 2 mm/year have been measured on steep mountains in high rainfall tropical regions.

Soil age and the influence of time on soil formation also refer to the development of pedological features in a soil profile once the regolith has been created. In this sense, the clock of soil formation starts ticking when a landslide exposes new rock to the weathering environment at the surface, when a flooding river deposits a new layer of sediment on its floodplain, when a glacier melts and dumps its load of mineral debris, when a landslide tumbles down a steep mountainside, or when a bulldozer cuts and fills a landscape to level a construction or mine-reclamation site.

Rates of Weathering. When we speak of a "young" or a "mature" soil, we are not so much referring to the age of the soil in years, as to the degree of weathering and profile development. Time interacts with the other factors of soil formation. For example, on a level site in a warm climate, with much rain falling on permeable parent material rich in reactive minerals, weathering and soil profile differentiation will proceed far more rapidly, yielding a more developed soil profile than on a site with steep slopes and resistant parent material in a cold, dry climate.

In a few instances, soils form so rapidly that the effect of time on the process can be measured in a human life span. For example, dramatic mineralogical, structural, and color changes occur within a few months to a few years when certain sulfide-containing materials are first exposed to air by excavation, wetland drainage, or sediment dredging (see Figure 2.32 and Sections 9.6 and 13.20). Under favorable conditions, organic matter may accumulate to form a darkened A horizon in freshly deposited, fertile alluvium in a mere decade or two. In some cases, incipient B horizons become discernible on humid-region mine spoils in as few as 40 years. Structural alteration and coloring by accumulated iron may form a simple B horizon within a few centuries if the parent material is sandy and the climate is humid. The same degree of B-horizon development would take much longer under conditions less favorable for weathering and leaching. The accumulation of silicate clays and the formation of blocky structure in B horizons usually become noticeable only after several thousand years. Developing in resistant rock, a mature, deeply weathered soil may be hundreds of thousands of years in the making (Figure 2.36).

[7]Recent work in New Zealand has provided new insights into how extremely fast rock weathering into soil material can keep ahead of the high rate of erosion on mountains in the wet tropics (Larson et al., 2014).

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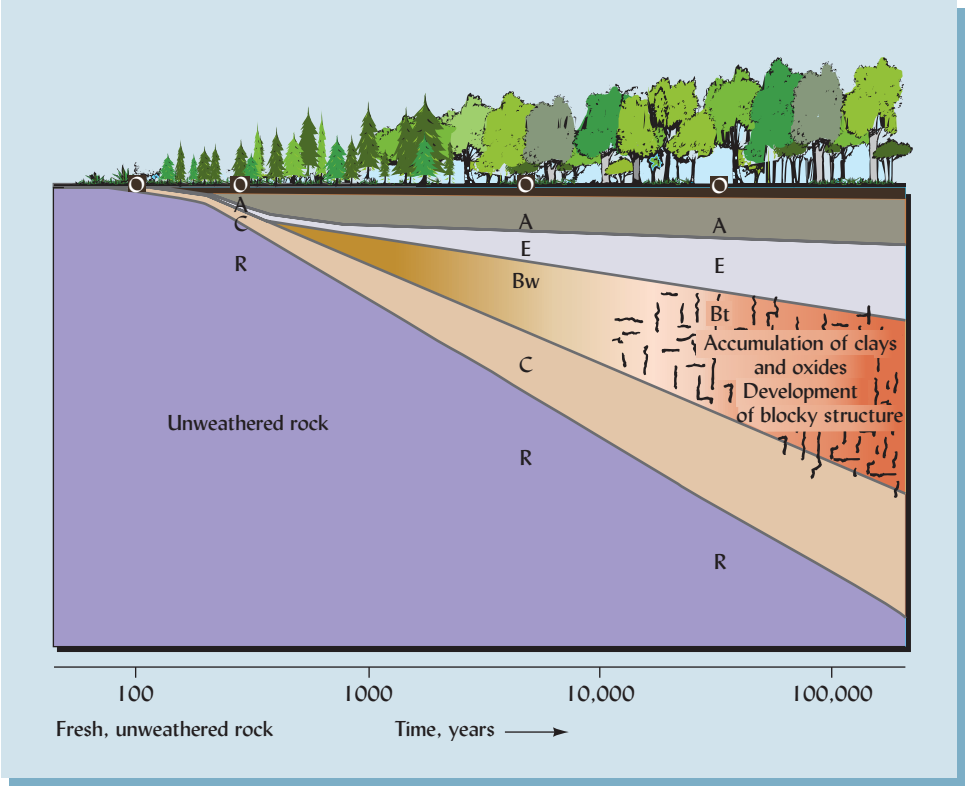

Figure 2.36 *Progressive stages of soil profile development over time for a residual igneous rock in a warm, humid climate that is conducive to forest vegetation. The time scale increases logarithmically from left to right, covering more than 100,000 years. Note that the mature profile (right side of this figure) expresses the full influence of the forest vegetation as illustrated in Figure 2.26. This mature soil might be classified as an Ultisol (see Section 3.14).*
(Diagram courtesy of Ray R. Weil)

Example of Soil Genesis over Time. Figure 2.36 is worth studying carefully; it illustrates changes that typically take place during soil development on residual rock in a warm, humid climate. During the first 100 years, lichens and mosses establish themselves on the bare exposed rock and begin to accelerate its breakdown and the accumulation of dust and organic matter. Within a few hundred years, grasses, shrubs, and stunted trees have taken root in a deepening layer of disintegrated rock and soil, adding greatly to the accumulation of organic materials and to the formation of the A and C horizons. During the next 10,000 years or so, successions of forest trees establish themselves and the activities of a multitude of tiny soil organisms transform the surface plant litter into a distinct O horizon. The A horizon thickens somewhat, becomes darker in color, and develops a stable granular structure. Soon, a bleached zone appears just below the A horizon as soluble weathering products, iron oxides, and clays are moved with water and organic acids percolating down from the litter layer. These transported materials begin to accumulate in a deeper layer, forming a B horizon. The process continues with more silicate clay accumulating and blocky structure forming as the B horizon thickens and becomes more distinct. Eventually, the silicate clays themselves break down, some silica is leached away, and new clays containing less silica form in the B horizon. These clays often become mixed or coated with oxides of iron and aluminum, causing the B horizon to take on a reddish hue. As the entire profile continues to deepen over time, the zone of weathered, unconsolidated rock may become many meters thick.

Chronosequence. Most soil-profile features develop so slowly that it is not possible to directly measure time-related changes in their formation. Indirect methods, such as carbon dating or the presence of fossils and human artifacts, must be turned to for evidence about the time required for different aspects of soil development to occur. In a different approach to studying the effects of time on soil development, soil scientists look for a **chronosequence**—a set of soils that share a common climate, parent material, slope, and community of organisms, but differ with regard to the length of time that the materials have been subjected to weathering and soil formation. A chronosequence can sometimes be found among the soils forming on alluvial terraces of differing age. The highest terraces have been exposed for the longest time, those in lower positions have been more recently exposed by the cutting action of the stream, and those on the current floodplain are the youngest, being still subject to periodic additions of new material.

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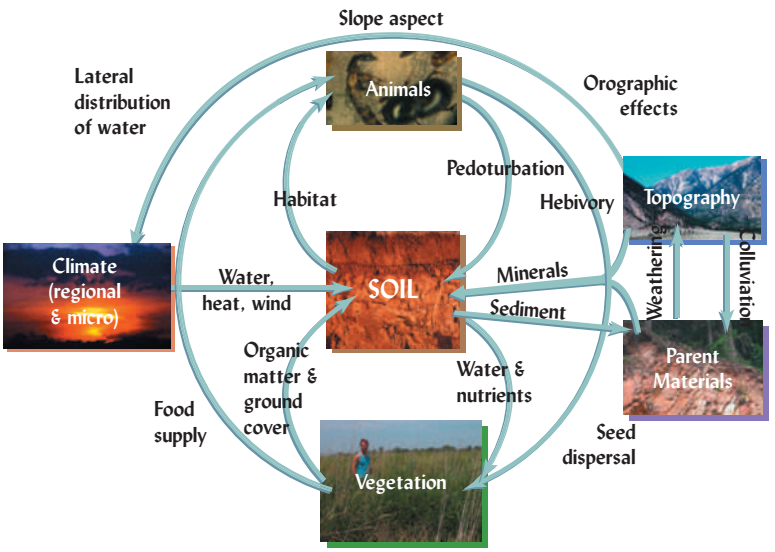

Figure 2.37 *Parent material, topography, climate, and organisms (vegetation and animals) do not act independently. Rather, they are linked in many ways and influence the formation of soils in concert. The influence of each factor shown is modified by the length of time it has been acting, although time as a soil-forming factor is not shown here.* [Adapted from Monger and Bestelmyer (2006)]

Interaction with Parent Materials. Residual parent materials have generally been subject to soil-forming processes for longer periods of time than have materials transported from one site to another. For example, soils forming on glacial materials have generally had far less time to develop than those soils farther south that escaped disturbance by the glaciers. Often the mineralogy and other properties of the "younger" soils in glaciated regions are more similar to those of their parent materials than is the case in the "older" soils of unglaciated regions. Nevertheless, comparisons are complicated because climate, vegetation, and parent material mineralogy also often differ between soils in glaciated and unglaciated areas.

The five soil factors of soil formation act simultaneously and interdependently to influence the nature of soils that develop at a site. Figure 2.37 illustrates some of the complex interactions that can help us predict what soil properties are likely to be encountered in a given environment. We will now turn our attention to the *processes* that cause parent materials to change into soils under the influence of these interacting soil-forming factors.

2.8 FOUR BASIC PROCESSES OF SOIL FORMATION[8]

The accumulation of regolith from the breakdown of bedrock or the deposition (by wind, water, ice, etc.) of unconsolidated geologic materials may precede or, more commonly, occur simultaneously with the development of the distinctive horizons of a soil profile. During the formation (**genesis**) of a soil from parent material, the regolith undergoes many profound changes. These changes are brought about by variations of four broad soil-forming processes (Figure 2.38). These four basic processes—often referred to as the soil-forming, or **pedogenic**, processes—help define what distinguishes soils from layers of sediment deposited by geologic processes. They are responsible for soil formation in all kinds of environments—even for **subaqueous soils** that develop in sediments under shallow water (see Box 2.2 and Table 2.5).

Transformations

Transformations occur when soil constituents are chemically or physically modified or destroyed and others are synthesized from the precursor materials. Many transformations involve weathering of primary minerals, disintegrating and altering some to form various kinds of silicate clays. As other primary minerals decompose, the decomposition products recombine into

[8]For the classic presentation of the processes of soil formation, see Simonson (1959). In addition, detailed discussion of these basic processes and their specific manifestations can be found in Birkeland (1999), Fanning and Fanning (1989), Buol et al. (2011), and Schaetzl and Anderson (2005).

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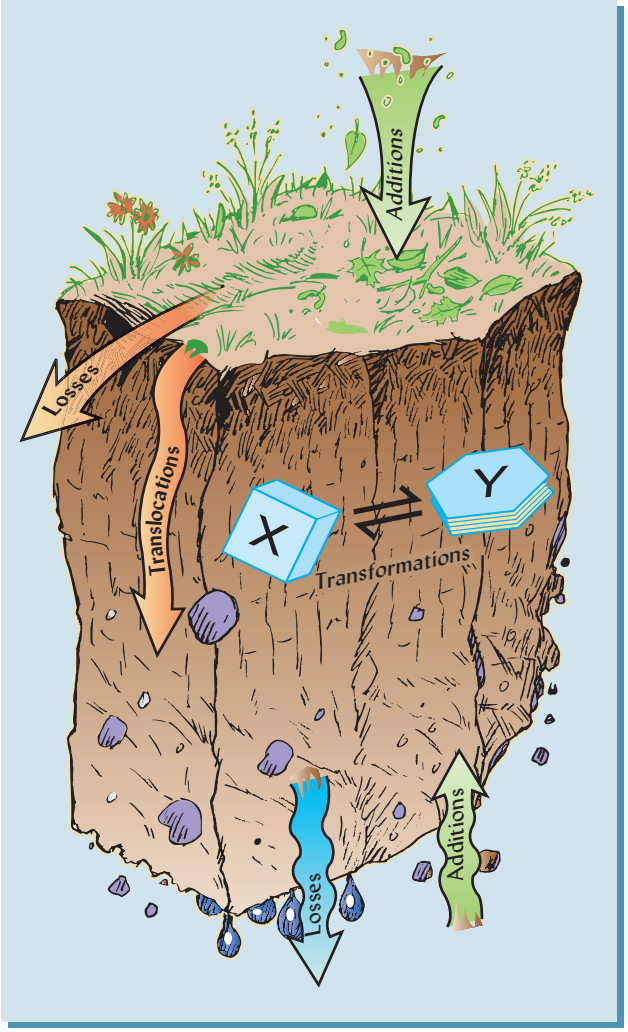

Figure 2.38 *A schematic illustration of additions, losses, translocations, and transformations as the fundamental processes driving soil-profile development.* (Diagram courtesy of Ray R. Weil)

new minerals that include additional types of silicate clays and hydrous oxides of iron and aluminum (see Figure 2.4). Other important transformations involve the decomposition of plant root and shoot litter to form soil organic matter. Still other transformations change the size (e.g., physical weathering to smaller particles) or arrangement (e.g., aggregation) of mineral particles.

Translocations

Translocations involve the movement of inorganic and organic materials laterally within a horizon or vertically from one horizon up or down to another. Water, either percolating down with gravity or rising up by capillary action (see Section 5.2), is the most common translocation agent. The materials moved within the profile include dispersed fine clay particles, dissolved salts, and dissolved organic substances. Translocations of materials by soil organisms also have a major influence on soil genesis. Important examples include incorporation of surface organic litter into the A and B horizons by certain earthworms, transport of B and C horizon material to the surface by mound-building termites, and the widespread burrowing actions of rodents.

Additions

Inputs of materials to the developing soil profile from outside sources are considered **additions**. A very common example is the input of organic matter from fallen plant leaves and sloughed-off roots (the carbon having originated in the atmosphere). Another ubiquitous addition is dust particles falling on the surface of the soil (wind may have blown these particles from a source just a few meters away or across an ocean). Still another example, common in arid regions, is the addition of salts or silica dissolved in the groundwater and deposited near

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or at the soil surface when the rising water evaporates. Animals and people can also contribute additions, such as manure and fertilizers.

Losses

Materials are lost from the soil profile by leaching to groundwater, erosion of surface materials, and volatilization of gases. Evaporation and plant use cause losses of water. Leaching and drainage cause the loss of water, dissolved substances such as salts or silica weathered from parent minerals, or organic acids produced by microorganisms or plant roots. Fire and biochemical reactions cause the loss of carbon, nitrogen, and sulfur as gases (Chapters 12 and 13). Erosion, a major loss agent, often removes the finer particles (humus, clay, and silt), leaving the surface horizon relatively sandier and less rich in organic matter than before. Grazing by animals or harvest by people can remove large amounts of both organic matter and nutrient elements.

These processes of soil genesis, operating under the influence of the environmental factors discussed previously, give us a logical framework for understanding the relationships between particular soils and the landscapes and ecosystems in which they function. In analyzing these relationships for a given site, ask yourself: What are the materials being added to this soil? What transformations and translocations are taking place in this profile? What materials are being removed? And how have the climate, organisms, topography, and parent material at this site affected these processes over time?

Soil-Forming Processes in Action: A Simplified Example

Consider the changes that might take place as a soil develops from a thick layer of relatively uniform calcareous loess parent material in a climate conducive to grass vegetation (Figure 2.39). Although some physical weathering and leaching of carbonates and salts may be necessary to allow plants to grow in certain parent materials, soil formation really gets started when plants become established and begin to provide *additions* of litter and root residues on and in the surface layers of the parent material. The plant residues are *transformed* by soil organisms into soil organic matter, including various organic acids. The accumulation of organic matter enhances the capacity of the soil to hold water and nutrients, providing positive feedback for accelerated plant growth and further organic buildup. Earthworms, ants, termites, and a host of smaller animals come to live in the soil and feed on the newly accumulating organic resources. In so doing, they accelerate the organic *transformations*, as well as promote the *translocation* of plant residues, loosening the mineral material as they burrow into the soil.

A-Horizon Development. The resulting organic–mineral mixture near the soil surface soon becomes the A horizon. It is darker in color and its chemical and physical properties differ from those of the original parent material. Individual soil particles in this horizon commonly clump together under the influence of organic substances to form granules, differentiating this layer from the deeper layers and from the original parent material. On sloping land, erosion may remove some materials from the newly forming upper horizon, retarding, somewhat, the progress of horizon development.

Formation of B and C Horizons. Carbonic and other organic acids are carried by percolating waters into the soil, where they stimulate weathering reactions. The acid-charged percolating water dissolves various minerals (a *transformation*) and leaches the soluble products (a *translocation*) from upper to lower horizons, where they may precipitate. This combination of transformation and translocation creates (eluvial) zones of depletion in the upper layers and (illuvial) zones of accumulation in the lower layers. The dissolved substances include both positively charged ions (cations; e.g., Ca^{2+}) and negatively charged ions (anions; e.g., CO_3^{2-} and SO_4^{2-}) released from the breakdown of minerals and organic matter. In semiarid and arid regions, precipitation of these ions produces horizons enriched in calcite ($CaCO_3$) or gypsum ($CaSO_4\ 2H_2O$), designated as a Bk layer in Figure 2.39.

As the process proceeds, the leached surface layer thickens, and the zone of Ca accumulation is moved downward to the maximum depth of water penetration. Where rainfall is great enough to cause significant drainage to the groundwater, some of the dissolved materials may be completely removed from the developing soil profile (*losses*), and the zone of accumulation

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BOX 2.2

SUBAQUEOUS SOILS—UNDERWATER PEDOGENESIS

Soil scientists are beginning to study soil profiles that develop under shallow water. In particular, the concept of soils has recently expanded to include the natural bodies that comprise sediment "landscapes" lying under up to 2 meters of water in ponds, lakes, and coastal estuaries and bays. These soils differ from wetlands that support emergent hydrophytic plants; subaqueous soils host only submerged aquatic vegetation (SAV—mainly aquatic grasses that are rooted but do not emerge above the water). Working from floating drill rigs, soil scientists have mapped distinct soil bodies in which the four basic soil-forming processes have created distinguishable horizons (Table 2.5).

Note the striking similarities to the soil-forming processes pictured in Figures 2.38 and 2.39. Understanding the different soils in the underwater landscape may help estuary managers to inventory and conserve coastal marine resources in much the same way that soils information helps managers of dry land to protect and optimize terrestrial resources

Table 2.5
SOIL-FORMING PROCESSES OBSERVED TO FORM SUBAQUEOUS SOILS IN SEDIMENTS WITH SUBMERGED VEGETATION UNDER SHALLOW WATER IN A COASTAL ESTUARY
Note the striking similarities to the soil-forming processes pictured in Figures 2.38 and 2.39. Understanding the different soils in the underwater landscape may help estuary managers to inventory and conserve coastal marine resources in much the same way that soils information helps managers of dry land to protect and optimize terrestrial resources

Process	Examples Observed in Subaqueous Soils
Additions	Calcium carbonates added from clam and oyster shells.
	Organic matter added from roots and leaves of aquatic vegetation.
	Mineral sediments washed in by currents.
Losses	Carbon lost by decomposition of organic matter.
	Surface mineral material washed away by storm currents.
Translocations	Oxygen moved into the profile by diffusion from seawater.
	Oxygen and organic material mixed into upper 15 cm by burrowing clams and tubeworms.
Transformations	Formation of humus-like organic matter by microbial processing of plant residues.
	Formation of the mineral pyrite from sulfate in the seawater and iron in the sediments.

Summarized from Demas and Rabenhorst (2001). For a review of subaqueous soils, see Rabenhorst and Stolt (2012). For updates on subaqueous soil mapping in the northeastern United States, see Turenne (2014)

may move below the reach of plant roots or be dissipated altogether. On the other hand, deep-growing plant roots may intercept some of these soluble weathering products and return them, through leaf- and litter-fall, to the soil surface, thus retarding somewhat the processes of acid weathering and horizon differentiation.

The weathering of primary minerals into clay minerals becomes evident only long after the dissolution and movement of Ca is well underway. The newly formed clay minerals may accumulate where they are formed, or they may move downward and accumulate deeper in the profile. As clay is removed from one layer and accumulates in another, adjacent layers become more distinct from each other, and a Bt horizon (one enriched in silicate clay) is formed. When the accumulated clay in the Bt horizon periodically dries out and cracks, block-like or prismatic units of soil structure begin to develop (see Figure 2.39 and Section 4.4). As the soil matures, the various horizons within the profile generally become more numerous and more distinctly different from each other.

2.9 THE SOIL PROFILE

Each location on the land surface has experienced a particular combination of influences from the five soil-forming factors, causing a different set of layers (horizons) to form in each part of the landscape, thus slowly giving rise to the natural bodies we call **soils**. Each soil is

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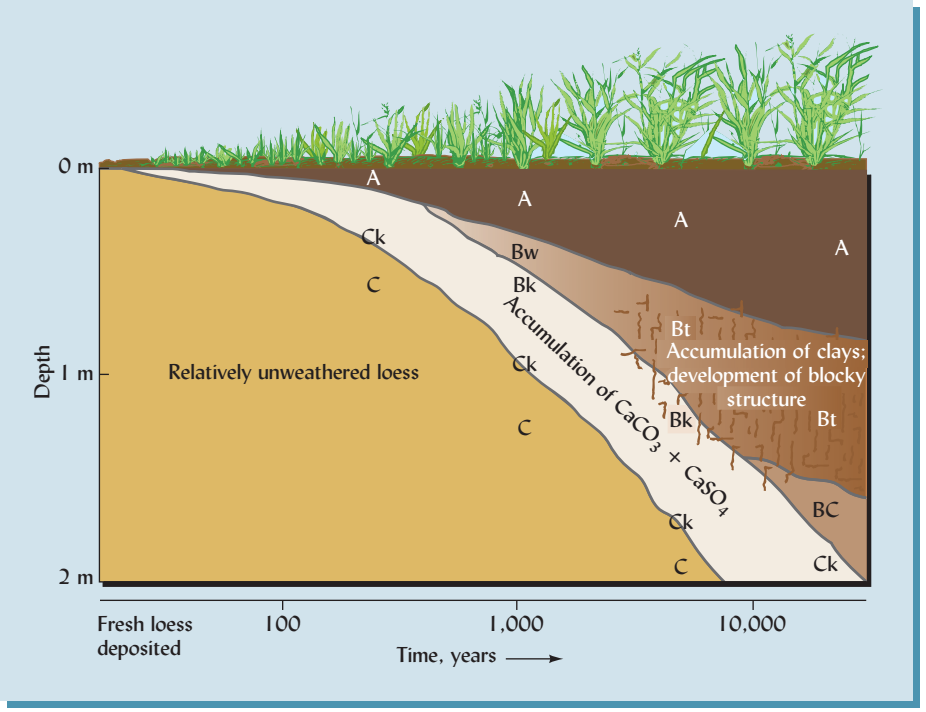

Figure 2.39 *Development of a hypothetical soil in about 2 m of uniform calcareous loess deposits where the warm subhumid climate is conducive to tall grass prairie vegetation. The time scale increases logarithmically from left to right, covering about 20,000 years. In the initial stages, rainwater, charged with organic acids from microbial respiration, dissolves carbonates from the loess and moves them downward to a zone of accumulation (Bk horizon). As this happens, plant roots take hold in the upper layer and add the organic matter necessary to create an A horizon. Ants, beetles, earthworms, and a host of smaller creatures take up residence and actively mix in surface litter and speed the release of nutrients from the minerals and plant residues. Over time the carbonate concentration zone moves deeper, the A horizon thickens, and noncalcareous B horizons develop as changes in color and structure occur in the weathering loess above the zone of carbonate accumulation. Eventually, silicate clay accumulates in the B horizon (giving it the designation Bt), both by stationary weathering of primary minerals and by traveling there with water percolating from the upper horizons. Compare the stages of development and rates of change to those illustrated in Figure 2.37 for a different parent material, vegetation, and climate. Note that the mature profile (right side of this figure) expresses the full influence of the grassland vegetation as illustrated in Figure 2.26. This mature soil would be classified as a Mollisol (see Section 3.12).* (Diagram courtesy of Ray R. Weil)

characterized by a given sequence of these horizons. A vertical exposure of this sequence is termed a **soil profile**. We will now consider the major horizons making up **soil profiles** and the terminology used to describe them.

The Master Horizons and Layers[9]

Six **master** soil horizons are commonly recognized and are designated using the capital letters O, A, E, B, C, and R (Figure 2.40). Subhorizon horizons may occur within a master horizon and these are designated by lowercase letters following the capital master horizon letter (e.g., Bt, Ap, or Oi).

[9]In addition to the six master horizons described in this section, **L** (limnic—Greek *limnē*, marsh), **W** (water), **V** (vesicular), and **M** (manufactured root-limiting subsoil layers) are also considered to be master horizons or layers. The L horizon occurs only in certain organic soils and includes layers of organic and mineral materials deposited in water or by aquatic organisms (e.g., diatomaceous earth, sedimentary peat, and marl). Layers of water (frozen or liquid) found within (not overlying) certain soil profiles are designated as W master horizons. The V horizons are layer-dominated non-connected, bubble-like pores that occur in or near the surface of desert soils. The M horizons occur mainly in urban soils in which manufactured root-impermeable materials, such as geotextile or asphalt, form a horizontal, near-continuous layer.

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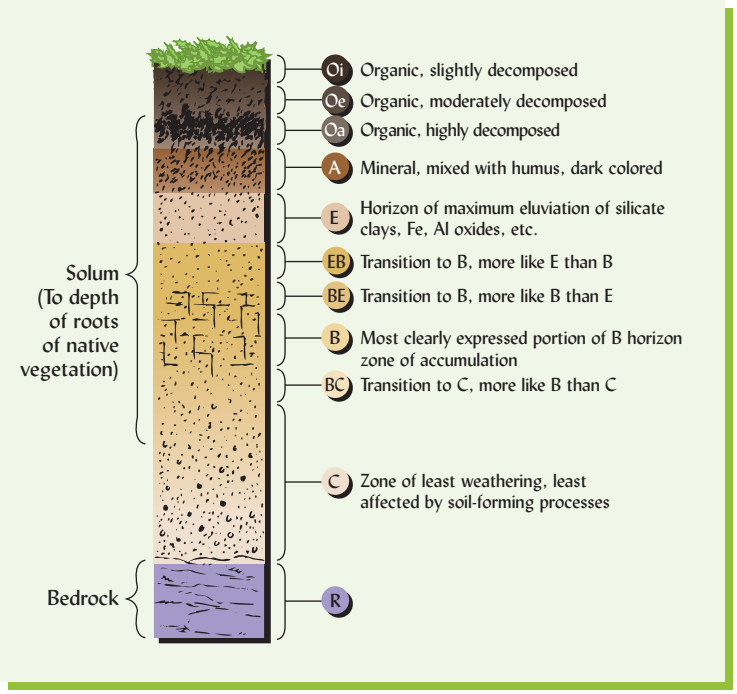

Figure 2.40 *Hypothetical mineral soil profile showing the major horizons that may be present in a well-drained soil in the temperate humid region. Any particular profile may exhibit only some of these horizons, and the relative depths vary. In addition, however, a soil profile may exhibit more detailed subhorizons than indicated here. The solum includes the A, E, and B horizons plus some cemented layers of the C horizon.*

O Horizons. The O group is comprised of organic horizons that generally form above the mineral soil or occur in an organic soil profile. They derive from dead plant and animal residues. Generally absent in grassland regions, O horizons usually occur in forested areas and are commonly referred to as the **forest floor** (see Figure 2.41). Often three subhorizons within the O horizon can be distinguished.

The **Oi horizon** is an organic horizon of **f*i*bric** materials—recognizable plant and animal parts (leaves, twigs, and needles), only slightly decomposed. (The Oi horizon is referred to as the *litter* or *L layer* by some foresters.)

The **Oe horizon** consists of **h*e*mic** materials—finely fragmented residues intermediately decomposed, but still with much fiber evident when rubbed between the fingers. (This layer corresponds to the *fermentation* or *F layer* described by some foresters.)

The **Oa horizon** contains **s*a*pric** materials—highly decomposed, smooth, amorphous residues that do not retain much fiber or recognizable tissue structures. (This is the *humidified* or *H layer* designated by some foresters.)

A Horizons. The topmost mineral horizons, designated A horizons, generally contain enough partially decomposed organic matter to give the soil a color darker than that of the lower horizons (Figure 2.42, *left*). In medium-textured soils, the A horizons are often coarser in texture, having lost some of the finer materials by translocation to lower horizons and by erosion.

E Horizons. These are zones of maximum leaching or ***eluviation*** (from Latin *ex* or *e*, out, and *lavere*, to wash) of clay, iron, and aluminum oxides, which leaves a concentration of resistant minerals, such as quartz, in the sand and silt sizes. An E horizon is usually found underneath the A horizon and is generally lighter in color than both the A horizon above it and the horizon below. Such E horizons are quite common in soils developed under forests where they occasionally occur directly under the O horizons (Figure 2.42, *right*). They rarely occur in soils developed under grassland.

B Horizons. B horizons form below an O, A, or E horizon and have undergone sufficient changes during soil genesis so that the original parent material structure is no longer discernable. In many B horizons, materials have accumulated, typically by washing *in* from the horizons above, a process termed **illuviation** (from the Latin *il*, in, and *lavere*, to wash). In humid regions,

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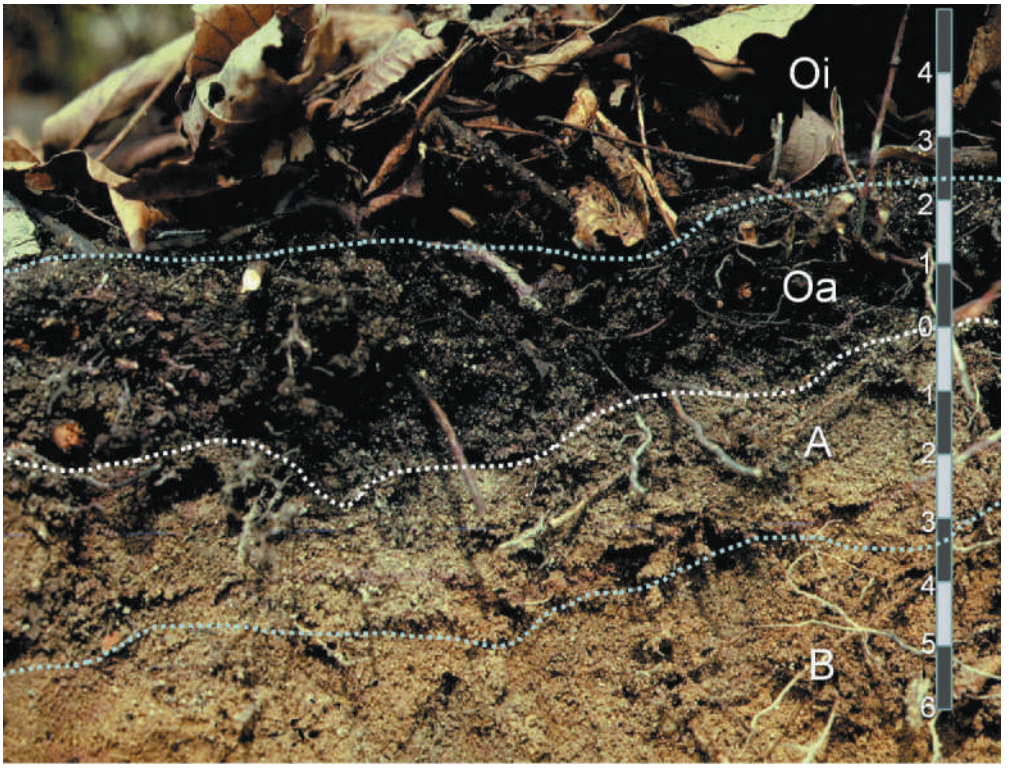

Figure 2.41 *The upper horizons of a soil formed under temperate forest vegetation. Note the accumulation of decaying organic material (O horizons) above a thin organic-enriched mineral A horizon, that in turn sit above a redder-colored B horizon. An E horizon, common in may forested soils, is absent in this profile. Scale in centimeters.* (Photo courtesy of Ray R. Weil)

Figure 2.42 *Examples of master soil horizons.* (Left) *A young sandy soil under grassy vegetation exhibits a marked accumulation of organic matter in the A horizon.* (Right) *Another sandy soil under forest vegetation has an O horizon of organic material directly over a bleached E horizon. Scales in centimeters.* (Photos courtesy of Ray R. Weil)

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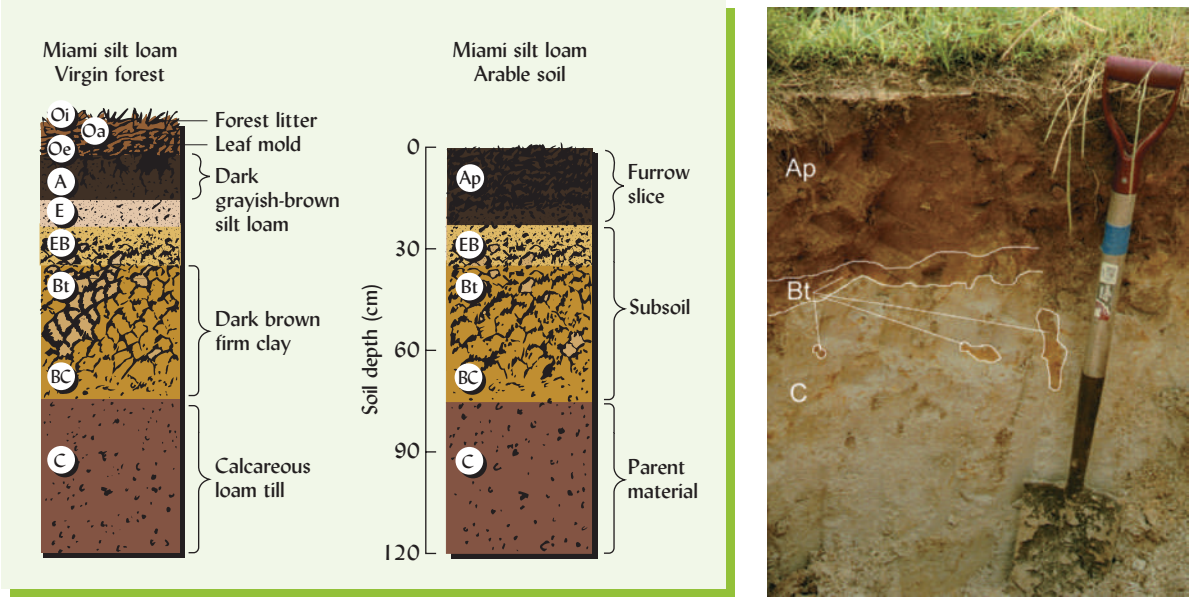

(a) (b) (c)

Figure 2.43 *Generalized profile of the Miami silt loam, one of the Alfisols of the eastern United States, before* (a) *and after* (b) *land is plowed and cultivated. Once the surface layers (O, A, and E) are mixed by tillage, they will form a new upper horizon termed the* Ap *(physically disturbed as by plowing)* horizon. *If erosion occurs, the O, A, and E horizons may disappear, at least in part, and some of the B horizon may be included in the tilled surface layer.* (c) *An Ultisol profile in Maryland, USA, so truncated by 300 years of erosion and tillage.* (Ray R. Weil)

B horizons are the layers of maximum accumulation of materials such as iron and aluminum oxides and silicate clays (Bt horizons), some of which may have illuviated from upper horizons and some of which may have formed in place. In arid and semiarid regions, calcium carbonate or calcium sulfate may accumulate in the B horizon (giving Bk and By horizons, respectively).

The B horizons are sometimes referred to loosely as the subsoil, although this is an imprecise term. In soils with shallow A horizons, part of the B horizon may become incorporated into the plow layer and thus become part of the topsoil (Figure 2.43). In other soils with deep A horizons, the plow layer or topsoil may include only the upper part of the A horizons, and the subsoil would include the lower part of the A horizon along with the B horizon. This emphasizes the need to differentiate between colloquial terms (*topsoil* and *subsoil*) and technical terms used by soil scientists to describe the soil profile.

C Horizon. The C horizon is the unconsolidated material underlying the solum (A and B horizons). It may or may not be the same as the parent material from which the solum formed. The C horizon is below the zones of greatest biological activity and has not been sufficiently altered by soil genesis to qualify as a B horizon. In dry regions, carbonates and gypsum may be concentrated in the C horizon. While loose enough to be dug with a shovel, C horizon material that retains some of the structural features of the parent rock or geologic deposits from which it formed is termed **saprolite** (see, e.g., the lower third of the profile shown in Figure 2.44). Its upper layers may in time become a part of the solum as weathering and erosion continue.

R Layers. These are consolidated rock, with little evidence of weathering (bottom of Figures 2.40 and 2.44).

Subdivisions Within Master Horizons

Often distinctive layers exist *within* a given master horizon, and these are indicated by a numeral *following* the letter designation. For example, if three different combinations of structure and colors can be seen in the B horizon, then the profile may include a sequence such as B1–B2–B3 (see Figure 2.44).

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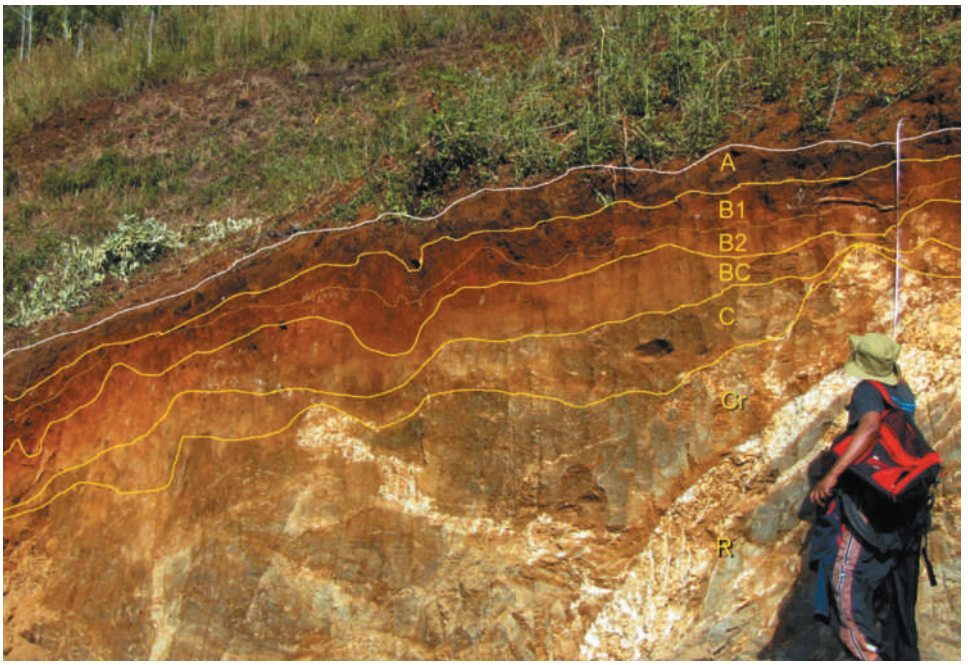

Figure 2.44 *A residual soil formed from gneiss parent rock in the Uluguru Mountains of Tanzania. Note the three B horizons, the variable depth of rock weathering, and the rock-like features retained in the Cr-horizon.* (Photo courtesy of Ray R. Weil)

If two different geologic parent materials (e.g., loess over glacial till) are present within the soil profile, the numeral 2 is placed *in front* of the master horizon symbols for horizons developed in the second layer of parent material. For example, a soil would have a sequence of horizons designated O–A–B–2C if the C horizon developed in glacial till whereas the upper horizons developed in loess.

Where a layer of mineral organic soil material was transported by *humans* (usually using machinery) from a source outside the pedon, the "caret" symbol (^) is inserted before the master horizon designation. For example, suppose a landscaping contractor hauls in and spreads a layer of sandy fill material over an existing soil in order to level a site. The resulting soil might eventually (after enough organic matter had accumulated to form an A horizon) have the following sequence of horizons: ^A-^C-2Ab-2Btb, where the first two horizons formed in the human-transported fill (hence the ^ prefixes), and the last two horizons were part of the underlying, now buried soil (hence the lower case "b" designations).

Transition Horizons

Transitional layers between the master horizons (O, A, E, B, and C) may be dominated by properties of one horizon but also have characteristics of another. The two applicable capital letters are used to designate the transition horizons (e.g., AE, EB, BE, and BC), the dominant horizon being listed before the subordinate one (e.g., Figure 2.41). Letter combinations with a slash such as E/B, are used to designate transition horizons where distinct parts of the horizon have properties of E while other parts have properties of B.

Subhorizon Distinctions

Since the capital letter designates the nature of a master horizon in only a very general way, specific horizon characteristics may be indicated by a lowercase letter following the master horizon designation. For example, three types of O horizons (Oi, Oe, and Oa) are indicated in the profile shown in Figure 2.40, which presents a commonly encountered sequence of horizons. Other subhorizon distinctions include special physical properties and the accumulation of particular materials such as clays and salts. A list of the recognized subhorizon letter designations and their meanings is given in Table 2.6. We suggest that you mark this table for future reference and study it now to get an idea of the distinctive soil properties that can be indicated by horizon designations. As mentioned previously, a Bt horizon is a B horizon characterized by clay accumulation (t from the German *ton*, meaning clay); likewise, in a Bk

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Table 2.6
SOME COMMON SUBHORIZON DISTINCTIONS WITHIN MASTER HORIZONS[a]

Lower Case Symbol	Distinction	Lower Case Symbol	Distinction
a	Highly decomposed organic matter	n	Accumulation of sodium
b	Buried soil horizon	o	Accumulation of iron and aluminum oxides
c	Concretions or nodules	p	Plowing or other disturbance
co	Coprogenous earth	q	Accumulation of silica
d	Dense unconsolidated materials	r	Weathered or soft bedrock
di	Diatomaceous earth	s	Illuvial organic matter and iron, aluminum oxides
e	Intermediately decomposed organic matter	se	Presence of sulfides
f	Frozen soil	ss	Slickensides (shiny clay wedges)
ff	Dry permafrost	t	Accumulation of silicate clays
g	Strong gleying (mottling)	u	Human-manufactured artifacts
h	Illuvial accumulation of organic matter	v	Plinthite (high iron, red material)
i	Slightly decomposed organic matter	w	Distinctive color or structure without clay accumulation
j	Jarosite (yellow sulfate mineral)	x	Fragipan (high bulk density, brittle)
jj	Cryoturbation (frost churning)	y	Accumulation of gypsum
k	Accumulation of carbonates	yy	Gypsum >50% of soil by mass
kk	Engulfment of carbonates, >50% of soil by mass	z	Accumulation of soluble salts
m	Cementation or induration		

[a]Based on information in Soil Survey Staff (2014)

horizon, carbonates (k) have accumulated. We have already used the suffixes i, a, and e to distinguish different types of O horizons.

The letter subhorizon designations are considered before any numerical subdivisions are applied. Thus the subdivision numbers start over with "1" if there is a change in the horizon letter designations; for example Bt1-Bt2-Btg1-Btg2 is a correctly labeled sequence, but Bt1-Bt2-Btg3-Btg4 is *not* correct. The significance of the subhorizon horizon designations will be discussed further in the next chapter.

Horizons in a Given Profile

It is not likely that the profile of any one soil will show all of the horizons that collectively are shown in Figure 2.40. The ones most commonly found in well-drained soils are Oi and Oe (or Oa) if the land is forested, A or E (or both, depending on circumstances), Bt or Bw, and C. Conditions of soil genesis will determine which horizons are present and their clarity of expression.

When a virgin (never-cultivated) soil is plowed and cultivated for the first time, the upper 15 to 20 cm becomes the plow layer or Ap horizon. Cultivation obliterates the original layered condition of the upper portion of the profile, and the Ap horizon becomes more or less homogeneous. In some soils, the A and E horizons are deeper than the plow layer (Figure 2.43*a*). In other cases where the upper horizons are quite thin, the plow line is just at the top of, or even down in, the B horizon.

In some cultivated land, serious erosion produces a **truncated profile** (Figure 2.43*b*, *c*). As the surface soil is swept away over the years, the plow reaches deeper and deeper into the profile. Hence, the plowed zone in many cases consists almost entirely of former B horizon

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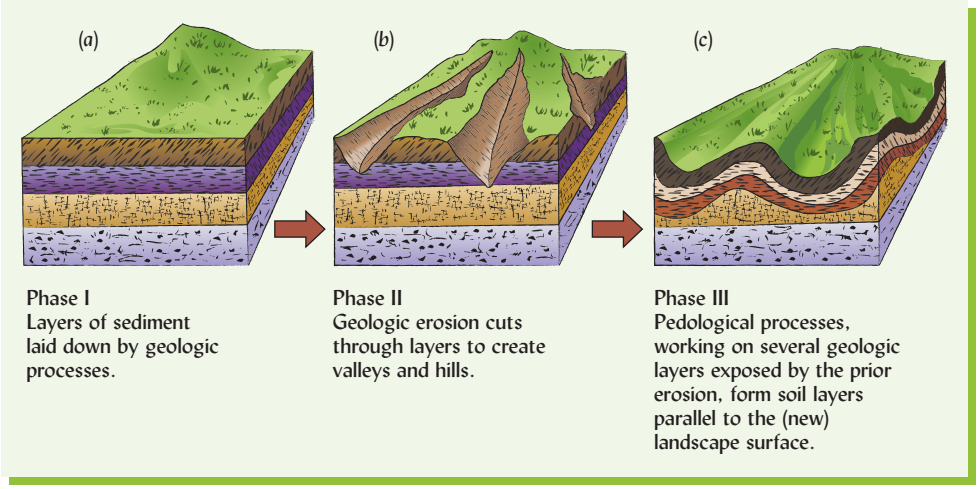

Figure 2.45 *Distinguishing between geologic layers (potential parent materials) and pedogenic layers (soil horizons).* (a) *Layers of sediment laid down by geologic processes, possibly forming different sedimentary rock layers.* (b) *The exposed land surface erodes by the action of water (or in dry environments, by wind) forming deep gullies that eventually become swales and valleys.* (c) *Once the landscape stabilizes, soils begin to form in the layers of geologic materials exposed by erosion. The pedogenic (soil-forming) processes cause the geologic material to differentiate into layers that parallel the new land surfaces.* (Diagram courtesy of Ray R. Weil)

material, and the C horizon is correspondingly near the surface. Comparison to a nearby non-eroded site can show how much erosion has occurred. Another, sometimes perplexing, profile feature is the presence of a buried soil (see Figure 2.46) resulting from natural or human action. In profile study and description, such a situation requires careful analysis.

Soil Genesis in Nature

Not every contrasting layer of material found in soil profiles is a **genetic horizon** that developed as a result of the processes of soil genesis such as those just described. The parent materials from which many soils develop contained contrasting layers *before* soil genesis started. For example, such parent materials as glacial outwash, marine deposits, or recent alluvium may consist of various layers of fine and coarse particles laid down by separate episodes of sedimentation (see Figure 2.45). Consequently, in characterizing soils, we must recognize not only the genetic horizons and properties that come into being during soil genesis, but also those layers or properties that may have been inherited from the parent material. Figure 2.46 illustrates how soil horizons that form during soil genesis and follow the surface topography of the land can develop in layers of contrasting materials previously laid down by geologic processes. This profile also exhibits many direct and indirect influences of humans as part of the *organisms* factor of soil formation—influences that are most strongly expressed in urban soils.

2.10 URBAN SOILS[10]

Urban land now accounts for nearly 3% of the earth's land surface. For the first time in human evolution, more than half of all people live in cities. Therefore, although human influences on soils long have had widespread importance, urban soils are taking on new significance. Soils occurring

[10]For a survey of soil properties in urban areas, see Pouyat et al. (2010). For an accessible review of a broad range of urban soils issues, see Bartens (2012).

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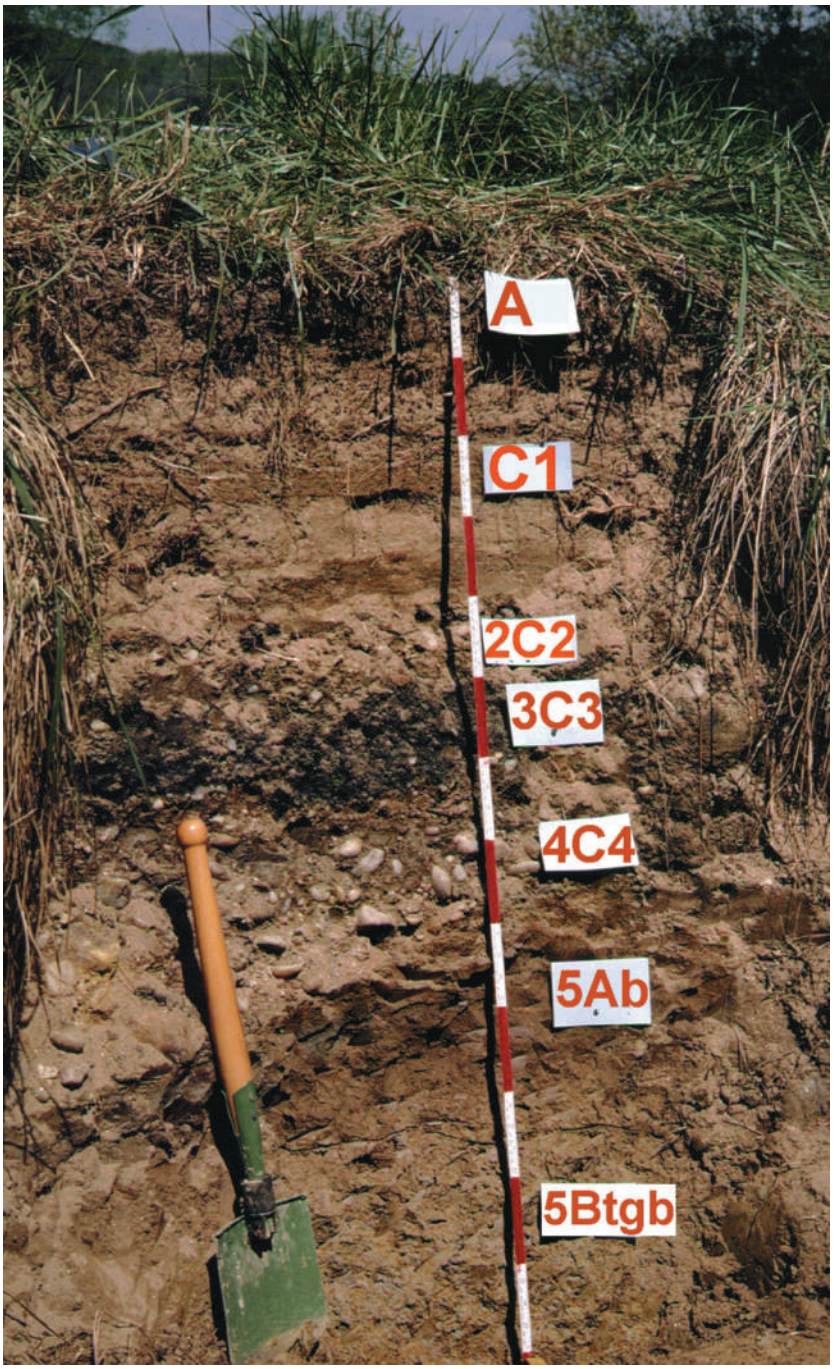

Figure 2.46 *A soil profile forming in recent alluvium in the Atlantic coastal plain, USA. The upper 80 cm of this profile has developed in recent alluvium laid down by occasional floods during the past 300–400 years. The A horizon is the result of soil formation, but the various C horizons differ because of geologic rather than soil-formation processes. Several of these layers show unique properties associated with the history of the past three or four centuries. The dark layer at about 50–60 cm depth contains abundant bits of charcoal. This charcoal was probably washed off the watershed slopes by heavy rains shortly after European settlers extensively deforested the area using slash-and-burn techniques to open the land for farming in the early 1700s. The layer just above the charcoal was laid down somewhat later and contains such artifacts as bits of antique glass from the late 1700s or 1800s. The layer below the charcoal was laid down prior to widespread European settlement. It contains numerous oyster shells that probably washed in from Native American encampments along the stream. Still deeper in the profile lies a buried soil. Part of a buried A horizon (Ab) and a buried Bg horizon (Bgb) are visible. These layers probably formed over a long period of time when the streambed was in a different location and the site was a poorly drained area with fine textured materials.* (Photo courtesy of Ray R. Weil)

in urban landscapes will be included in discussions throughout the text, but here we will give special consideration to some of the issues relevant to the formation and morphology of such soils.

Pedological Properties Unique to Urban Soils

Urban soils are often heavily influenced by human bioturbation—that is, the soil materials are reworked by human activities ranging from shoveling to bulldozing as the land surface is excavated and graded. Commonly, materials are trucked in from nearby excavations or from off-site locations and spread as a fill layer (typically an ^Au horizon) on top of the existing soil. This process also creates various buried horizons (typically designated 2Ab, 2Cb, etc.).

In addition, urban profiles may include layers of any of the following: geotextile fabric, sand or gravel, clay compacted to engineering standards, building rubble and artifacts such

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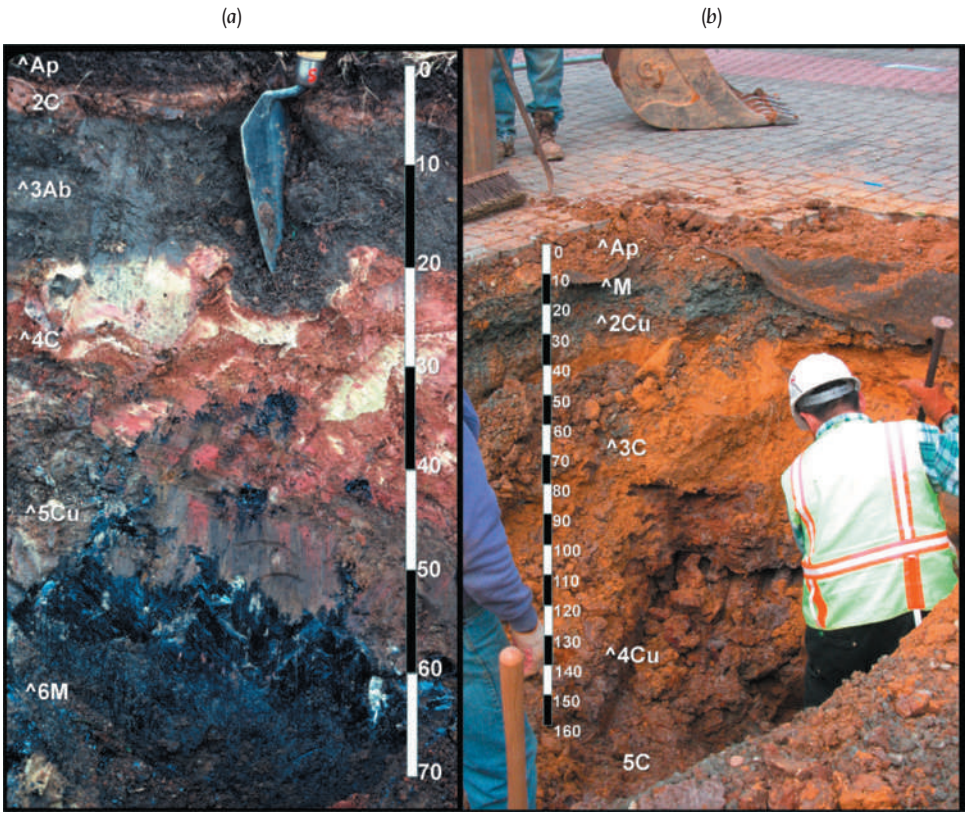

Figure 2.47 *Some features of highly human-modified urban soils.* (Left) *An soil in a landscaped area showing a thin layer of topsoil (^Ap) spread over a thin layer of sediment from recent erosion (2C) over a thick buried A horizon spread in an earlier grading operation. An "M" master horizon (see footnote 9) is present at 55–75 cm where a thick layer of impermeable asphalt was buried.* (Right) *An engineered urban soil under a layer of paving stones set in sand. The M horizon in this profile consists of a layer of geotextile that is impermeable to roots and was installed to prevent the sand layer from shifting down into the layer of gravel and artifacts (^2Cu) below it. This is underlain by a thick sand layer (^3C) for drainage and then a layer of compacted clay and rubble fill (^4Cu). The buried remnants of the original soil C horizon can be seen at 150 cm depth.*
(Photos courtesy of Ray R. Weil)

as nails, metal and plastic scrapes, broken glass, bricks and concrete blocks, and chunks of gypsum wallboard and paving asphalt (Figure 2.47*a*). In residential areas, "topsoil" may be brought in from other areas and spread, usually in a very thin layer, on top of unrelated materials comprising the deeper soil layers. For many urban soils, the various human-influenced processes occurred sporadically during different periods of time. This type of history often results in several buried horizons (Figure 2.47*b*). In other cases, these processes were carefully orchestrated to "engineer" a new soil for particular purposes. For example, the final cover for solid waste landfills is a special case of an engineered urban soil profile that includes an impermeable layer of compact clay covered by a drainage layer of coarse sand and topped with a layer of loamy material to support protective vegetation (see Section 18.9).

Physical Properties Unique to Urban Soils

Urban soils can become highly compacted because of the weight of structures and pavement and human or vehicular traffic both during and after the placement of soil materials. Another unique feature of urban soils is the abrupt boundaries between materials of highly contrasting texture and porosity, such as layers of gravel buried beneath layers of clay. While these properties may be desirable from the point of view of engineering function, they can create major problems for water percolation and tree root growth.

Chemical Properties Unique to Urban Soils

The chemical properties of soils in urban areas may or may not exhibit much of a relationship to the properties expected from local climatic or parent material conditions. For instance, due to the influence of concrete and cement, some urban soils are surprisingly alkaline in high rainfall areas where acid soils are expected. Soils that occur beneath sealed pavements may receive little percolating water even in high rainfall environments, and therefore may be less thoroughly leached of soluble constituents than might be expected for the local climate.

Urban soils are commonly contaminated with various anthropogenic substances; lead, other toxic metals, organic petroleum-based of contaminants, and deicing salts are commonly of concern. In some cases, rusting iron nails or dissolving concrete react to reduce the mobility and

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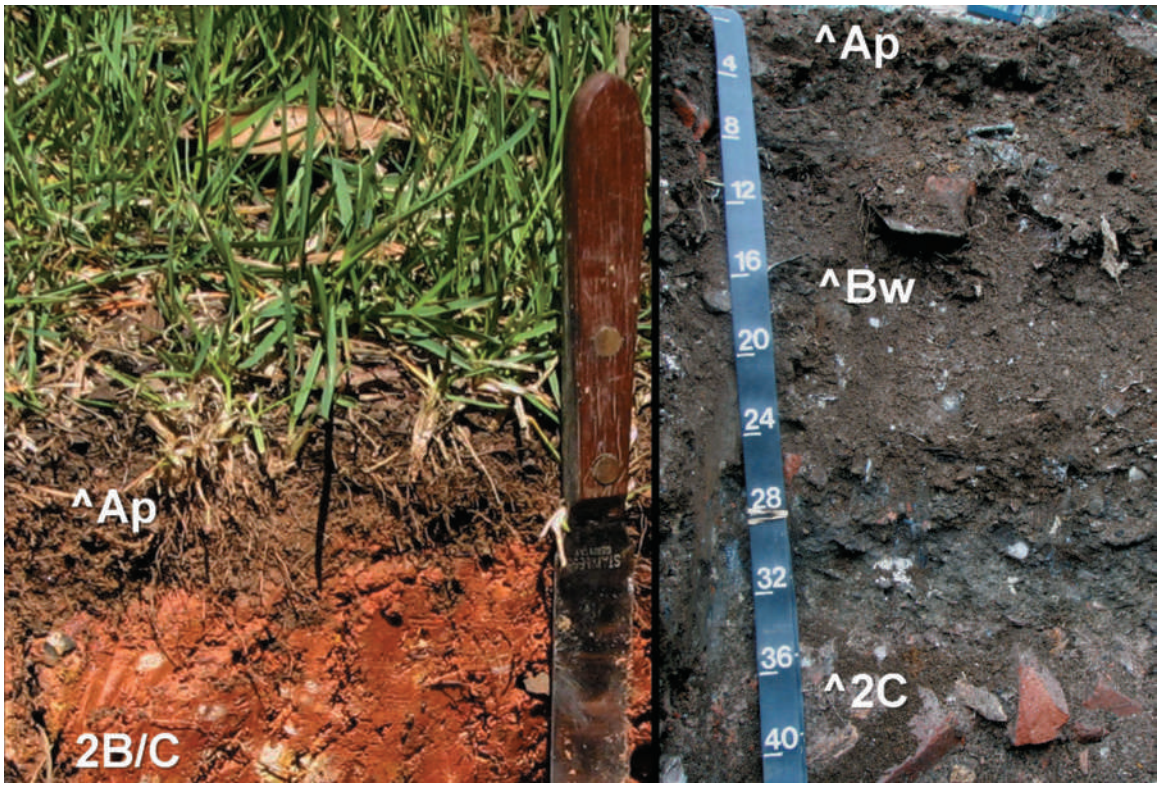

Figure 2.48 *Two highly human-modified but nonengineered urban soils* (Left) *The upper horizons of a soil in a residential area (spatula handle is 10 cm long). A thin layer of "topsoil" was spread on top of very acid, infertile clayey B and C horizon material left after the land surface was graded by heavy machinery. The lawn grasses grew poorly because the soil favorable for rooting is only 2–5 cm thick.* (Right) *A soil profile formed in construction debris mixed with excavated soil materials used as fill. This is a LaGuardia soil (scale in inches 1 inch = cm) mapped as part of the soil survey of Bronx River watershed, New York City in the USA. About 35–75 percent of the volume of the B and C horizons consists of coarse fragments—chunks of concrete, brick, glass, and metal can be seen. The B horizon had developed enough change in soil structure to be designated a Bw horizon.* (Left photo courtesy of Ray R. Weil; right photo courtesy of the Natural Resource Conservation Service)

toxicity of such contaminants as lead. Contamination with nutrients and pathogens from biological wastes is also prevalent in urban soils, either from failed or under-engineered sewage disposal systems, or from stray animals, rats, and from dogs whose owners fail to clean up after them.

Biological Properties Unique to Urban Soils

Urban soils differ from other soils because they are less likely to be covered with a vegetative community reflecting the local climate and parent materials. Except in parks areas allowed to maintain remnants of natural vegetation communities, most vegetated urban soils support exotic species planted by humans and maintained against natural succession processes. Many urban soils are kept nearly bare by erosion or trampling, whereas others are covered by impermeable pavements. Thus plant inputs of carbon that normally "feed" the soil ecosystem are likely to be highly variable or even absent. The compaction and low organic matter levels may make the soils very inhospitable to both plant roots and microbial communities. In many of the vegetated areas, only a very thin layer of suitable rooting medium may have been spread on top of the chemically and physically inhospitable materials (Figure 2.48). Even the atmosphere in urban areas may impact plants and soil microorganisms in both positive and negative ways. High levels of ozone and other pollutants reduce plant growth and subsequent carbon inputs into the soil, while high levels of carbon dioxide accompanied by warmer temperatures due to "the urban heat island effect" may increase both plant growth and microbial decomposition rates compared to what would occur in nonurban situations.

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2.11 CONCLUSION

The parent materials from which soils develop vary widely around the world and from one location to another only a few meters apart. Knowledge of these materials, their sources or origins, mechanisms for their weathering, and means of transport and deposition are essential to understanding soil genesis.

Soil formation is stimulated by *climate* and living *organisms* acting on *parent materials* over periods of *time* and under the modifying influence of *topography*. These five major factors of soil formation determine the kinds of soil that will develop at a given site. When all of these factors are the same at two locations, the kind of soil at these locations should be the same. Although all five factors interact and work together, at times one factor's influence dominates over the others. For example, climate probably dominates in Arctic soils, whereas organisms (namely humans) may dominate in urban soils.

Soil genesis starts when layers or horizons not present in the parent material begin to appear in the soil profile. Organic matter accumulation in the upper horizons, the downward movement of soluble ions, the synthesis and downward movement of clays, and the development of specific soil particle groupings (structure) in both the upper and lower horizons are signs that the process of soil formation is under way. As we have learned, soil bodies are dynamic in nature. Their genetic horizons continue to develop and change. Consequently, in some soils horizon differentiation has only begun, whereas in others it is well advanced.

The four general processes of soil formation (gains, losses, transformations, and translocations) and the five major factors influencing these processes provide us with an invaluable logical framework in site selection and in predicting the nature of soil bodies likely to be found on a particular site. Conversely, analysis of the horizon properties of a soil profile can tell us much about the nature of the climatic, biological, and geological conditions (past and present) at the site.

Characterization of the horizons in the profile leads to the identity of a soil individual, which is then subject to classification—the topic of our next chapter.

STUDY QUESTIONS

1. What is meant by the statement, *weathering combines the processes of destruction and synthesis?* Give an example of these two processes in the weathering of a primary mineral.
2. How is water involved in the main types of chemical weathering reactions?
3. Explain the weathering significance of the ratio of silicon to aluminum in soil minerals.
4. Give an example of how parent material may vary across large geographic regions on one hand but may also vary within a small parcel of land on the other.
5. Name the five factors affecting soil formation. With regard to each of these factors of soil formation, compare a forested Rocky Mountain slope to the semiarid grassland plains far below.
6. How do *colluvium*, *glacial till*, and *alluvium* differ in appearance and agency of transport?
7. What is *loess*, and what are some of its properties as a parent material?
8. Give two specific examples for each of the four broad processes of soil formation.
9. Assuming a level area of granite rock was the parent material in both cases, describe in general terms how you would expect two soil profiles to differ, one in a warm, semiarid grassland and the other in a cool, humid pine forest.
10. For the two soils described in question 5, make a profile sketch using master horizon symbols and subhorizon suffixes to show the approximate depths, sequence, and nature of the horizons you would expect to find in each soil.
11. Visualize a slope in the landscape near where you live. Discuss how specific soil properties (such as colors, horizon thickness, types of horizons present, etc.) would likely change along the toposequence of soils on this slope.
12. Imagine a soil pit dug in a vacant brown field in an old city industrial area. The horizons you observe include, from the soil surface down: (1) 19 cm of dark-colored organic enriched loamy material with nails and broken glass embedded in it; (2) 32 cm of sandy loam with bits of red brick, some broken glass, some rusting metal pieces, and rusty red and yellow stains on most of the sand grain surfaces giving the layer a yellow-red color; (3) 15cm of dark brown silt loam material rich in organic matter with an abrupt boundary to; (4) 50 cm of light brown silty clay loam material with clay coatings in the cracks between blocky chunks of soil material. Draw this profile in a simple diagram and label the four layers with master horizon and subhorizon letters and other appropriate symbols to indicate your best interpretation of soil formation at this site.

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REFERENCES

Bartens, J., N. Basta, S. Brown, C. Cogger, B. Dvorak, B. Faucette, P. Groffman, G. Hettairachchi, K. McIvor, R. Pouyat, G. Toor, and J. Urban. 2012. "Soils in the city." *Crop Soils Agronomy News*, **57**:4–13.

Binkley, D., and O. Menyailo (eds.). 2005. *Tree Species Effects on Soils: Implications for Global Change*. Kluwer Academic Publishers, Dordrecht.

Birkeland, P. W. 1999. *Soils and Geomorphology*. 3rd ed. Oxford University Press, New York.

Black, H. C. 1994. *Animal Damage Management Handbook*. General Technical Report PNW-GTR-332. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Buol, S. W., R. J. Southard, R. C. Graham, and P. A. McDaniel. 2011. *Soil Genesis and Classification*. 6th ed. Wiley-Blackwell, New York, 560 p.

Craft, C. B., and C. J. Richardson. 1998. "Recent and long-term soil accretion and nutrient accumulation in the everglades." *Soil Science Society of America Journal.*, **62**:834–843.

Daniels, W. L., G. R. Whittecar, and C. H. Carter, III. 2007. Conversion of potomac river dredge sediments to productive agricultural soils. Thirty Years of SMCRA and Beyond. American Society of Mining and Reclamation, Gillette, WY. http://www.asmr.us/Publications/Conference%20Proceedings/2007/0183-Daniels-VA.pdf

Demas, G. P., and M. C. Rabenhorst. 2001. "Factors of subaqueous soil formation: A system of quantitative pedology for submerged environments." *Geoderma*, **102**:189–204.

Fanning, D. S., and C. B. Fanning. 1989. *Soil: Morphology, Genesis, and Classification*. John Wiley and Sons, New York.

Heimsath, A. M. 2014. "Limits of soil production?" *Science*, **343**:617–618.

Herwartz, D., A. Pack, B. Friedrichs, and A. Bischoff. 2014. "Identification of the giant impactor theia in lunar rocks." *Science*, **344**:1146–1150.

Hilgard, E. W. 1921. *Soils: Their Formation, Properties, Composition, and Plant Growth in the Humid and Arid Regions*. Macmillan, London.

Jenny, H. 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. Originally published by McGraw-Hill; Dover, Mineola, NY.

Jenny, H. 1980. *The Soil Resource—Origins and Behavior*. Ecological Studies, Vol. 37. Springer-Verlag, New York.

Larsen, I. J., P. C. Almond, A. Eger, J. O. Stone, D. R. Montgomery, and B. Malcolm. 2014. "Rapid soil production and weathering in the southern alps, New Zealand." *Science*, **343**:637–640.

Logan, W. B. 1995. *Dirt: The Ecstatic Skin of the Earth*. Riverhead Books, New York.

McEwen, A. S., L. Ojha, C. M. Dundas, S. S. Mattson, S. Byrne, J. J. Wray, S. C. Cull, S. L. Murchie, N. Thomas, and V. C. Gulick. 2011. "Seasonal flows on warm martian slopes," *Science*, **333**:740–743.

Monger, H.C., and B.T. Bestelmeyer. 2006. "The soil-geomorphic template and biotic change in arid and semi-arid ecosystems." *Journal of Arid Environments* **65**:207–218.

National Science Foundation. 1975. "All that unplowed, land," *Mosaic*, **6**:17–21. National Science Foundation, Washington, DC.

Ojha, L., M.B. Wilhelm, S.L. Murchie, A.S. McEwen, J.J. Wray, J. Hanley, M. Masse, and M. Chojnacki. 2015. "Spectral evidence for hydrated salts in recurring slope lineae on mars," *Nature Geoscience*, Published online 28 September. doi 10.1038/ngeo2546

Pouyat, R. V., K. Szlavecz, I. D. Yesilonis, P. M. Groffman, and K. Schwarz. 2010. "Chemical, physical, and biological characteristics of urban soils," pp. 119–152, in J. Aitkenhead-Peterson and A. Volder (eds.), *Urban Ecosystem Ecology*, Vol. 55. Amer. Soc. Agronomy, Crop Sci. Soc. Amer., Soil Sci. Soc. Amer., Madison, WI.

Rabenhorst, M. C., and M. H. Stolt. 2012. "Subaqeuous soils: Pedogenesis, mapping and applications," pp. 173–204, in H. Lin (ed.), *Hydropedolgy: Synergistic Integration of Soil Science and Hydrology*. Academic Press, Amsterdam.

Richter, D. D., and D. Markewitz. 2001. *Understanding Soil Change*. Cambridge University Press, Cambridge.

Schaetzl, R., and S. Anderson. 2005. *Soils—Genesis and Geomorphology*. Cambridge University Press, Cambridge.

Schlee, J. S. 2000. *Our Changing Continent*. U.S. Geological Survey Information Services. http://pubs.usgs.gov/gip/continents/ (posted 02/15/2000; verified 10 April 2007).

Simonson, R. W. 1959. "Outline of a generalized theory of soil genesis," *Soil Sci Soc Amer Proc.*, **23**:152–156.

Soil Survey Staff. 2014. *Keys to Soil Taxonomy*. 12th ed. [Online]. Available by United States Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1252094&ext=pdf

Thorn, C. 1978. "A preliminary assessment of the geomorphic role of pocket gophers in the Alpine zone of the Colorado front range," *Geografiska Annaler*, **60A**:3–4.

Turenne, J. 2014. Subaqueous soils page [Online]. Available by Nesoil.com http://nesoil.com/sas/index.htm (verified 6 June 2014).

van Breemen, N., and A. C. Finzi. 1998. "Plant–soil interactions: Ecological aspects and evolutionary implications," *Biogeochemistry*, **42**:1–19.

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The late Roy Simonson investigates a soil profile. (Photo © Rodale Institute)

3 Soil Classification

It is embarrassing not to be able to agree on what soil is. In this the pedologists are not alone. Biologists cannot agree on a definition of life and philosophers on philosophy.
—*Hans Jenny*, The Soil Resource: Origin and Behavior

We classify things in order to make sense of our world. We do it whenever we call things by group names, based on their important properties. Imagine a world without classifications. Imagine surviving in the woods knowing only that each plant was a plant, not which are edible by people, which attract wildlife, or which are poisonous. Imagine surviving in a city knowing only that each person was a person, not a child or an adult, a male or a female, a police officer, a hoodlum, a friend, a teacher, a potential date, or any of the other categories into which we classify people. So, too, our understanding and management of soils and terrestrial systems would be hobbled if we knew only that a soil was a soil. How could we organize our information about soils? How could we learn from others' experience or communicate our knowledge to clients, colleagues, or students?

From the time crops were first cultivated humans noticed differences in soils and classified them according to their suitability for different uses. Farmers used descriptive names such as *black cotton soils*, *rice soils*, or *olive soils*. Other soil names still in common use today suggest the parent materials from which the soils are formed: *limestone soils*, *piedmont soils*, and *alluvial soils*. Such terms may convey some valuable meaning to local users, but they are inadequate for helping us to organize our scientific knowledge of soils or for defining the relationships among the soils of the world.

In this chapter we will learn how soils are classified as natural bodies on the basis of their profile characteristics, not merely on the basis of their suitability for a particular use. Such a soil classification system is essential to foster global communications about soils among soil scientists and all people concerned with the management of land and the conservation of the soil resource. Soil classification allows us to take advantage of research and experience at one location to predict the behavior of similarly classified soils at another location. Soil names such as Histosols or Vertisols conjure up similar mental images in the minds of soil scientists everywhere, whether they live in Europe, Japan, China, the United States, or elsewhere. A goal of the classification system is to create a universal language of soils that enhances communication among users of soils around the world.

3.1 CONCEPT OF INDIVIDUAL SOILS

Compared to most sciences, the organized study of soils is rather young, having begun in the 1870s when the Russian scientist V. V. Dokuchaev and his associates first conceived the idea that soils exist as natural bodies in nature. Russian soil scientists soon developed a system

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for classifying natural soil bodies, but poor international communications and the reluctance of some scientists to acknowledge such radical ideas delayed the universal acceptance of the natural bodies concept. In the United States, it was not until the late 1920s that C. F. Marbut of the U.S. Department of Agriculture (USDA), one of the few scientists who grasped the concept of soils as natural bodies, developed a soil classification scheme based on these principles.

The natural body concept of soils recognizes the existence of individual entities, each of which we call *a soil.* Just as human individuals may be grouped according to characteristics such as gender, height, intelligence, or hair color, soil individuals having one or more characteristics in common may be grouped together. In turn, we may aggregate these groups into higher-level categories of soils, each having some characteristic that sets them apart from the others. Increasingly broad soil groups are defined as one moves up the classification pyramid from *a soil* to *the soil.*

Pedon and Polypedon[1]

There are seldom sharp demarcations between one soil individual and another. Rather, properties gradually change from one soil individual to an adjacent one. The gradation in soil properties can be compared to the gradation in the wavelengths of light in a rainbow. The change is gradual, and yet we differentiate between what we call green and what we call blue. Soils in the field are heterogeneous; that is, the profile characteristics are not exactly the same at any two points within the soil individual you may choose to examine. Consequently, it is necessary to characterize a soil individual in terms of an imaginary three-dimensional unit called a ***pedon*** (rhymes with "head on," from the Greek *pedon*, ground; see Figure 3.1). It is the smallest sampling unit that displays the full range of properties characteristic of a particular soil.

Pedons occupy from about 1 to 10 m^2 of land area. Because it is what is actually examined during field investigation of soils, the pedon serves as the fundamental unit of soil classification.

However, a soil unit in a landscape usually consists of a group of very similar pedons, closely associated together in the field. Such a group of similar pedons, or a ***polypedon***, is of sufficient size to be recognized as a landscape component termed a ***soil individual***.

All the soil individuals in the world that have in common a suite of soil profile properties and horizons that fall within a particular range are said to belong to the same ***soil series***. A soil series, then, is a class of soils, not a soil individual, in the same way that *Pinus sylvestris* is a species of tree, not a particular individual tree. Tens of thousands of soil series have been characterized and comprise the basic units used to classify the world's soils. As we shall see in

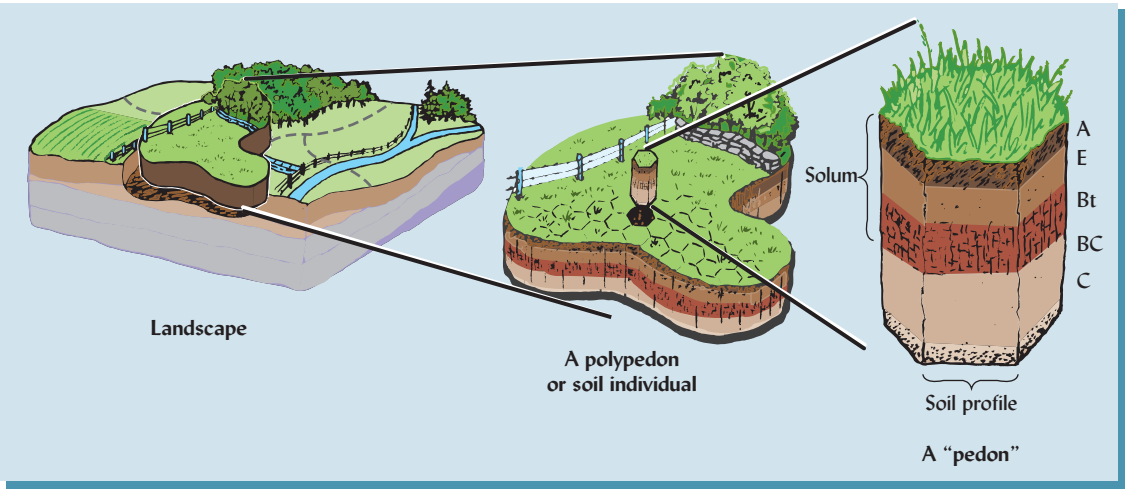

Figure 3.1 *A schematic diagram to illustrate the concept of pedon and of the soil profile that characterizes it. Note that several contiguous pedons with similar characteristics are grouped together in a larger area (outlined by broken lines) called a* polypedon *or soil* individual. *Several soil individuals are present in the landscape on the left.* (Diagram courtesy of Ray R. Weil)

[1]Although widely used, the polypedon concept is not without its critics. See Ditzler (2005).

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Section 19.5, units delineated on detailed soil maps are not purely one soil, but are usually named for the soil series to which *most* of the pedons within the unit belong.

Groupings of Soil Individuals

In the concept of soils, the most specific extreme is that of a natural body called *a soil*, characterized by a three-dimensional sampling unit (pedon), related groups of which (polypedons) are included in a soil individual. At the most general extreme is *the soil*, a collection of all these natural bodies that is distinct from deep water, solid rock, and other natural parts of the Earth's crust. Hierarchical soil classification schemes generally group soils into classes at increasing levels of generality between these two extremes.

Many cultures have traditional names for various classes of soils that help convey the people's collective knowledge about their soil resources (see Box 3.1). Scientific classification of soils began in the late 1800s stemming from the work of Dokuchaev in Russia (see Section 2.2). Australia, Brazil, Canada, China, the United Kingdom, Russia, and South Africa are among the countries that have developed and continue to use their own national soil classification systems.[2] To provide a global vocabulary for communicating about soils and a reference by which various national soil classification systems can be compared and correlated, scientists working through the Food and Agriculture Organization of the United Nations have developed a three-tier classification system known as the World Reference Base for Soils (see Appendix Table A.1). At the highest level, the world's soils are classified into 32 Soil Reference Groups that are differentiated mainly by the pedogenic process (such as the accumulation of clay in the subsoil) or parent material (such as volcanic ash) that is most responsible for creating the soil properties that typify the particular group. The system also uses an extensive list of prefix qualifiers that can provide a second tier of more specific classes within a Soil Reference Group. The prefix qualifiers include typical types found within a Soil Reference Group, as well as intergrades that indicate similarity to one of the 31 other Soil Reference Groups. A third tier of detail is provided by another list of suffix qualifiers that indicates specific soil properties and features.

In 1951 the Soil Survey Staff of the USDA began a long collaboration with soil scientists from many other countries aimed at devising a classification system comprehensive enough to address all soils in the world, not just those in the United States. First published in 1975, the resulting system, *Soil Taxonomy*, is used in the United States and approximately 50 other countries. Both the World Reference Base for Soils and Soil Taxonomy are widely used in international publications. However, to avoid the confusion of dealing with two quite different systems, Soil Taxonomy will be employed consistently throughout this text.

3.2 SOIL TAXONOMY: A COMPREHENSIVE CLASSIFICATION SYSTEM[3]

Soil Taxonomy provides a hierarchical grouping of natural soil bodies. The system is based on *soil properties* that can be objectively observed or measured, rather than on presumed mechanisms of soil formation. To encourage international acceptance, Soil Taxonomy is not based on any one national language. Instead, the system uses a unique nomenclature that connotes the major characteristics of the soils in question.

Bases of Soil Classification

Although one of the objectives of *Soil Taxonomy* is to group soils that are similar in their genesis, the specific criteria used to place soils in these groups are based on properties observable in soil profile as it is found today.

[2]See Appendix A for summaries of the World Reference Base for Soils and the Canadian and Australian Systems of Soil Classification. For more information on other national systems and their interrelationships, see Eswaran et al. (2003) and for scientific as well as indigenous "folk" soil classifications see chapters in Arnold et al. (2012).

[3]For the latest updates in Soil Taxonomy, see Soil Survey Staff (2014). For a complete description of *Soil Taxonomy* see Soil Survey Staff (1999). The first edition of *Soil Taxonomy* was published as Soil Survey Staff (1975).

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BOX 3.1

ETHNOPEDOLOGY: HOW LOCAL PEOPLE CLASSIFY THEIR SOILS[a]

For thousands of years, most societies were primarily agricultural, and almost everyone worked with soils on a daily basis. Raw survival, on a personal and community level, depended on the food that could be coaxed from the different soils that people found in their environment. By trial and error, people learned which soils were best suited to various crops and which responded best to different kinds of management. As farmers passed their observations and traditions from one generation to the next, they summarized their knowledge about soils by developing unique systems of soil classification. In some regions this local knowledge about soils helped shape agricultural systems that were sustainable for centuries. For example, formal Chinese soil classification goes back two millennia. In Beijing one may still visit the most recent (built in 1421) of a series of large sacrificial altars covered with five differently colored types of soils representing five regions of China (listed here with Soil Taxonomy names in parentheses): (1) whitish saline soils (Salids) from the western deserts, (2) black organic-rich soils (Mollisols) from the north, (3) blue-grey waterlogged soils (e.g., Aquepts) from the east, (4) reddish iron-rich soils (Ultisols) from the south, and (5) yellow soils (Inceptisols) from the central loess plateau.

Local languages often reflect a sophisticated and detailed knowledge of how soils differ from one another. The interdisciplinary study of *Ethnopedology* has documented many hitherto underappreciated indigenous classification systems that classify soils using soil color, texture, hardness, moisture, organic matter, and topography, as well as other soil properties (Figure 3.2). Most of these properties are those observable in the surface horizon, the part of the soil with which farmers come into daily contact. In this respect, the local classifications differ from most scientific classification schemes, as the latter focus on the subsurface horizons (as indicated in Figure 1.17). Rather than viewing this as a weakness, the two approaches can be seen as complementary.

History teaches us that people may rapidly degrade their new land and water resources when they move to an environment that is radically different from what they are used to. Whether these newcomers are Europeans settling the North American continent, lowland African tribes migrating into mountainous regions, or development specialists attempting to transfer technology from one country to another, they generally lack sufficient knowledge of the local soils to allow them to manage the resource in a sustainable way. Indigenous soil classification, reflecting knowledge gained over many generations of living in the local environment, can help and is too important to ignore when planning rural development projects.

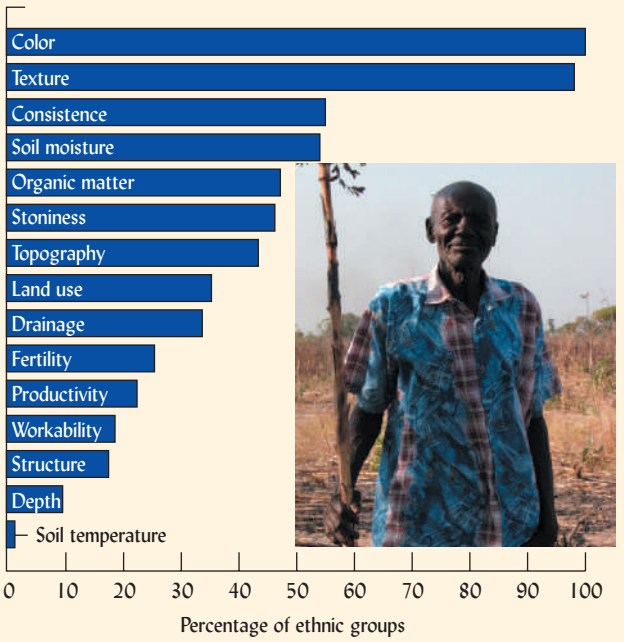

Figure 3.2 *Soil characteristics used in soil classification among 62 ethnic groups around the world.* [Data from Barrera-Bassols et al. (2006); photo courtesy of Ray R. Weil]

[a]For a brief review of the study of local soil classifications, see Talawar and Rhoades (1998). For a summary of ancient Chinese soil classification, see Gong et al. (2003).

Criteria for *Soil Taxonomy* involve most of the chemical, physical, and biological properties presented in this text. A few examples are moisture and temperature status throughout the year, as well as color, texture, and structure of the soil. Chemical and mineralogical properties, such as the contents of organic matter, clay, iron (Fe) and aluminum (Al) oxides, silicate clays, salts, the pH, the percentage *base saturation*,[4] and soil depth are other important criteria for classification. While many of the properties used may be observed in the field, others require precise measurements on samples taken to a sophisticated laboratory. This precision makes the system more objective, but in some cases may make the proper classification of a soil quite expensive and time-consuming.

[4]The percentage base saturation is the percentage of the soil's negatively charged sites (cation exchange capacity) that are satisfied by attracting nonacid (or *base*) cations (such as Ca^{2+}, Mg^{2+}, and K^{+}) (see Section 9.3).

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Diagnostic Surface Horizons of Mineral Soils

The presence or absence of certain layers, termed ***diagnostic soil horizons***, helps determine where to place a soil in the classification system. Diagnostic horizons that occur at the soil surface are called ***epipedons*** (from the Greek *epi*, over, and *pedon*, soil). The epipedon includes the upper part of the soil darkened by organic matter, the upper eluvial horizons, or both. It may include part of the B horizon if the latter is significantly darkened by organic matter. Eight are recognized (Table 3.1), but only five occur naturally over wide areas. Two of the others, anthropic and plaggen, result from intensive human use. They are common in parts of Europe and Asia where soils have been modified by people for many centuries.

Table 3.1
MAJOR FEATURES OF DIAGNOSTIC HORIZONS IN MINERAL SOILS USED FOR DIFFERENTIATION AT THE HIGHER LEVELS OF *SOIL TAXONOMY*
The asterisks (*) indicate the five epipedons that are naturally occurring over wide areas.

Diagnostic Horizon (and Typical Genetic Horizon Designation)	Major Features
Surface horizons = epipedons	
Anthropic (A)	Human-transported or modified materials, with artifacts, or high phosphorus or puddled condition (rice paddies)
Folistic (O)	Organic horizon saturated for less than 30 days per normal year
Histic (O)*	Very high in organic content, wet during some part of year
Melanic (A)*	Thick, black, high in organic matter (>6% organic carbon), common in volcanic ash soils
Mollic (A)*	Thick, dark-colored, high base saturation, well-developed structure
Ochric (A)*	Too light-colored, low organic content or thin to be mollic; may be hard and massive when dry
Plaggen (A)	Human-made sod-like horizon created by years of manuring, often with artifacts and spade marks
Umbric (A)*	Similar to mollic except low base saturation
Subsurface horizons	
Agric (A or B)	Organic and clay accumulation just below plow layer resulting from cultivation
Albic (E)	Light-colored, clay and iron and aluminum oxides mostly removed
Anhydritic (By)	Accumulation of anhydrite ($CaSO_4$)
Argillic (Bt)	Silicate clay accumulation
Calcic (Bk)	Accumulation of carbonates of calcium and/or magnesium
Cambic (Bw, Bg)	Altered by physical movement, structure development, or by chemical reactions, generally nonilluvial
Duripan (Bqm)	Hard pan, strongly cemented by silica
Fragipan (Bx)	Brittle pan, usually loamy textured, dense, coarse prisms
Glossic (E)	Whitish eluvial horizon that tongues into a Bt horizon
Gypsic (By)	Accumulation of gypsum ($CaSO_4 \cdot 2H_2O$)
Kandic (Bt)	Accumulation of low-activity clays
Natric (Btn)	Argillic, high in sodium, columnar or prismatic structure
Oxic (Bo)	Highly weathered, primarily mixture of Fe, Al oxides and nonsticky-type silicate clays
Petrocalcic (Ckm)	Cemented calcic horizon
Petrogypsic (Cym)	Cemented gypsic horizon
Placic (Csm)	Thin pan cemented with iron alone or with manganese and organic matter
Salic (Bz)	Accumulation of salts
Sombric (Bh)	Organic matter accumulation
Spodic (Bh, Bs)	Organic matter, Fe and Al oxide accumulation
Sulfuric (Cj)	Highly acid with Jarosite mottles

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The ***mollic epipedon*** (Latin *mollis,* soft) is a mineral surface horizon noted for its dark color associated with its accumulated organic matter (>0.6% organic C throughout), for its thickness (generally >25 cm), and for its softness even when dry. It has a high base saturation greater than 50%. Mollic epipedons are moist at least three months a year when the soil temperature is usually 5 °C or higher to a depth of 50 cm. These epipedons are characteristic of soils developed under grassland (Figure 3.3, *left*).

The ***umbric epipedon*** (Latin *umbra*, shade; hence, dark) has the same general characteristics as the mollic epipedon except the percentage base saturation is lower. This mineral horizon commonly develops in areas with somewhat higher rainfall and where the parent material has lower content of calcium and magnesium.

The ***ochric epipedon*** (Greek *ochros*, pale) is a mineral horizon that is either too thin (see Figure 3.3, *right*), too light in color, or too low in organic matter to be either a mollic or umbric horizon. It is usually not as deep as the mollic or umbric epipedons. As a consequence of its low organic matter content, it may be hard and massive when dry.

The ***melanic epipedon*** (Greek *melas*, melan, black) is a mineral horizon that is very black in color due to its high organic matter content (organic carbon >6%). It is characteristic of soils high in such minerals as allophane, developed from volcanic ash. It is more than 30 cm thick and is extremely light in weight and fluffy (low bulk density) for a mineral soil.

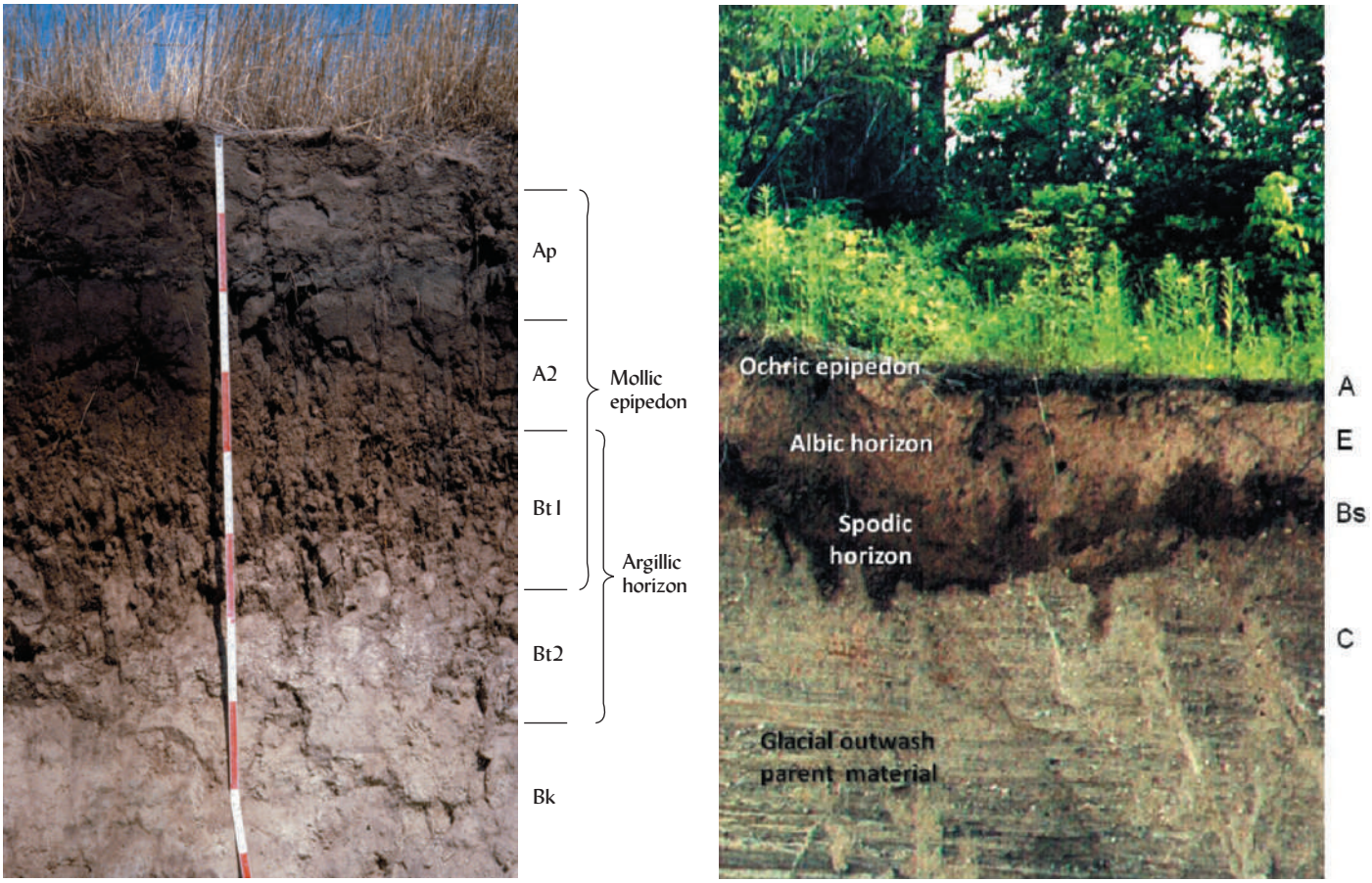

Figure 3.3 *Two soil profile illustrating five diagnostic horizons.* (Left) *The* mollic *epipedon* (*a diagnostic horizon*) *in this soil includes genetic horizons designated Ap, A2, and Bt1, all darkened by the accumulation of organic matter. A subsurface diagnostic horizon, the argillic horizon, overlaps the mollic epipedon. The* argillic *horizon is the zone of illuvial clay accumulation* (*Bt1 and Bt2 horizons in this profile*)*. Scale marked every 10 cm.* (Right) *The thin, dark* ochric *epipedon at the surface of this sandy soil typifies the A horizon under acid forest vegetation. It is underlain by a light-colored eluviated* albic *horizon, under which a wavy dark layer of illuvial humus and iron has accumulated to form a* spodic *horizon. The parent material, glacial outwash, can be seen in lower part of the profile. The mollic and spodic horizons are diagnostic for soils in the orders Mollisols and Spodosols, respectively.* (Photos courtesy of Ray R. Weil)

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The ***histic epipedon*** (Greek *histos*, tissue) is a 20- to 60-cm-thick layer of ***organic soil materials***[5] overlying a mineral soil. Formed in wet areas, the histic epipedon is a layer of peat or muck with a black to dark brown color and a very low bulk density.

Diagnostic Subsurface Horizons

Many subsurface diagnostic horizons are used to characterize different soils in *Soil Taxonomy* (Figure 3.4). Each diagnostic horizon provides a characteristic that helps place a soil in its proper class in the system. We will briefly discuss a few of the more commonly encountered subsurface diagnostic horizons.

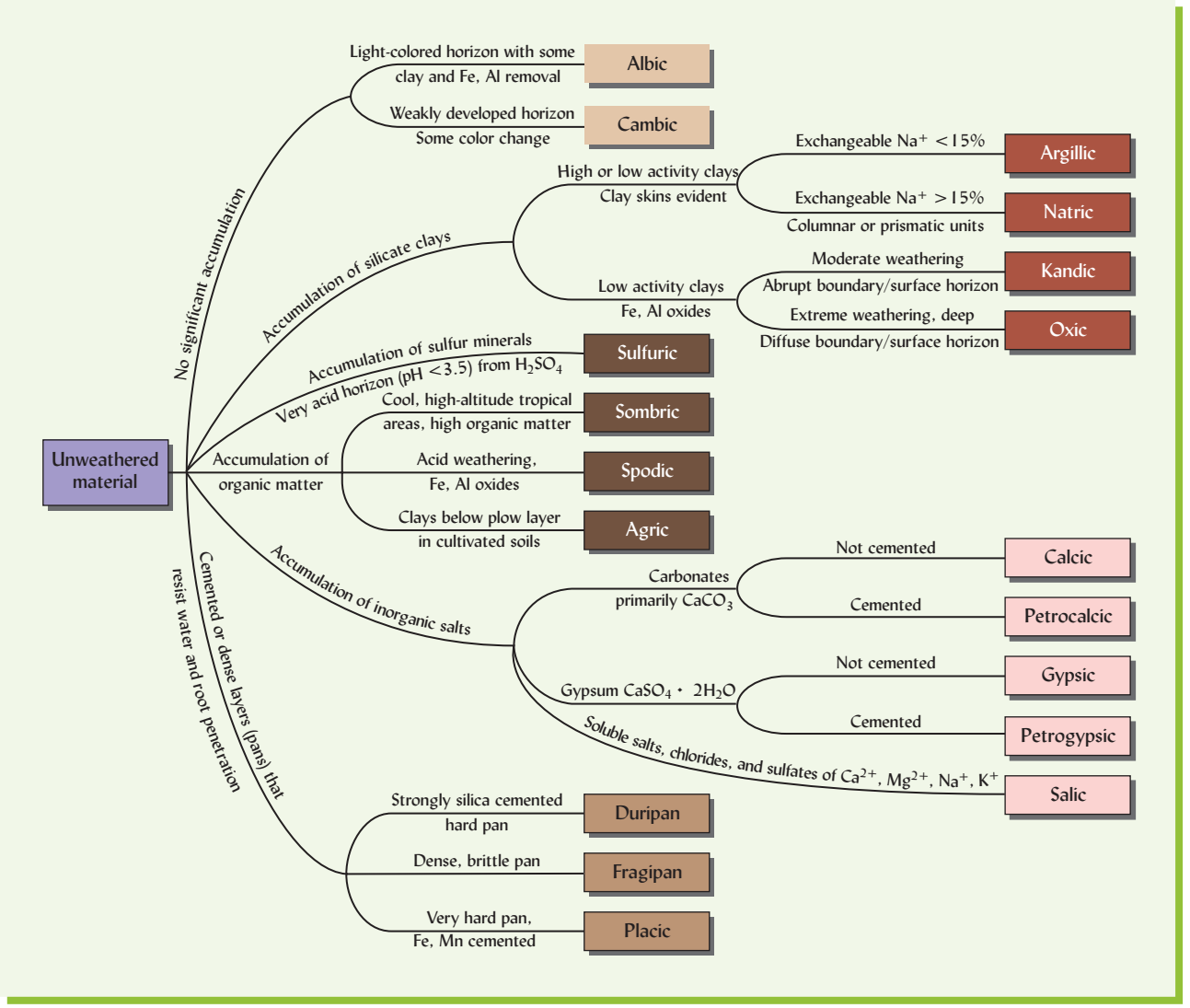

Figure 3.4 *Names and major distinguishing characteristics of major subsurface diagnostic horizons. Among the characteristics emphasized is the accumulation of silicate clays, organic matter, iron and aluminum oxides, calcium compounds, and soluble salts, as well as materials that become cemented or highly acidified, thereby constraining root growth. The presence or absence of these horizons plays a major role in determining in which class a soil falls in* Soil Taxonomy. *See Chapter 8 for a discussion of low- and high-activity clays.*

[5]*Organic soil material*, such as peat and muck, may consist almost entirely of organic matter, but it is technically defined as containing more than a certain *minimum amount of organic matter* as follows: If the material is not water-saturated in its natural state, its organic matter content must be at least 35% (about 200 g/kg organic carbon). If it is water-saturated during part of the year in its natural state, then the minimum organic matter content varies with the amount of clay in the material, ranging from 20% (120 g/kg organic carbon) if no clay is present to 30% (180 g/kg organic carbon) if the clay content exceeds 600 g/kg. For a discussion of the relationship between organic matter and organic carbon, see Section 12.4 and the footnote in Table 12.1.

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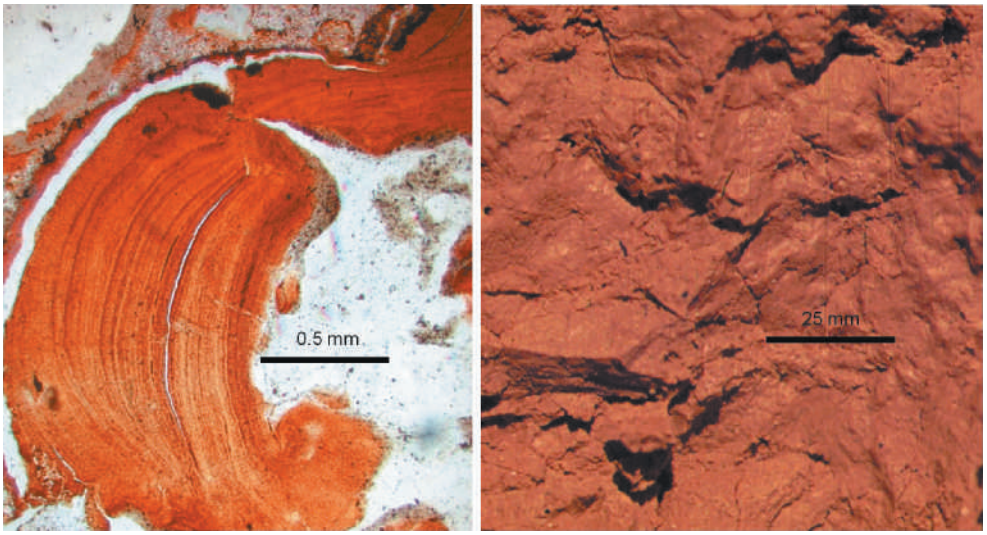

Figure 3.5 *The argillic subsurface diagnostic horizon is characterized by the accumulation of silicate clay, some of which has illuviated into the B horizon from soil layers higher in the profile. The illuvial movement of clay results in the deposition of thin coatings of clay on ped and pore surfaces. These "clay skins" or "argillans" can be seen under a petrographic microscope with plain polarized light* (left) *and with the naked eye as shiny clay coatings* (right). [Photos courtesy of Carlos Dorransoro Fernandez, University of Granda, Spain (left) and Ray R. Weil (right)]

The **argillic horizon** is a subsurface accumulation of silicate clays that have moved downward from the upper horizons or have formed in place. An example is shown in Figure 3.3 (*left*). The clays often are found as coatings on pore walls and surfaces of the structural groupings. The coatings usually appear as shiny surfaces or as clay bridges between sand grains. Termed *argillans* or *clay skins*, they are concentrations of clay translocated from upper horizons (see Figure 3.5).

The **natric horizon** likewise has silicate clay accumulation (with clay skins), but the clays are accompanied by more than 15% exchangeable sodium on the colloidal complex and by columnar or prismatic soil structural units. The natric horizon is found mostly in arid and semiarid areas. Examples are shown in Figures 4.13*e* and 10.18.

The **kandic horizon** has an accumulation of iron and aluminum oxides as well as low-activity silicate clays (e.g., kaolinite), but clay skins need not be evident. The clays are low in activity as shown by their low cation-holding capacities (<16 cmol*c*/kg clay). The epipedon that overlies a kandic horizon has commonly lost much of its clay content (see Figure 3.6).

The **oxic horizon** is a highly weathered subsurface horizon that is very high in iron and aluminum oxides and in low-activity silicate clays (e.g., kaolinite). The cation-holding capacity is <16 cmol*c*/kg clay. The horizon is at least 30 cm thick and has <10% weatherable minerals in the fine fraction. It is generally physically stable, crumbly, and not very sticky, despite its high clay content. It is found mostly in humid tropical and subtropical regions (see Figure 2.11, *left*).

The **spodic horizon** is an illuvial horizon that is characterized by the accumulation of colloidal organic matter and aluminum oxide (with or without iron oxide). It is commonly found in highly leached forest soils of cool humid climates, typically on sandy-textured parent materials (see Figure 3.3, *right*).

The **sombric horizon** is an illuvial horizon, dark in color because of high organic matter accumulation. It has a low degree of base saturation and is found mostly in the cool, moist soils of high plateaus and mountains in tropical and subtropical regions (Figure 3.7).

The **albic horizon** is a light-colored eluvial horizon that is low in clay and oxides of iron and aluminum. These materials have largely been moved downward from this horizon (see Figure 3.3, *right*).

A number of horizons have accumulations of salt-like chemicals that have leached from upper horizons in the profile. **Calcic horizons** contain an accumulation of carbonates (mostly $CaCO_3$) that often appear as white chalk-like nodules (see the Bk horizon in the lower part of the profile shown in Figure 3.3, *left*). **Gypsic horizons** have an accumulation of gypsum

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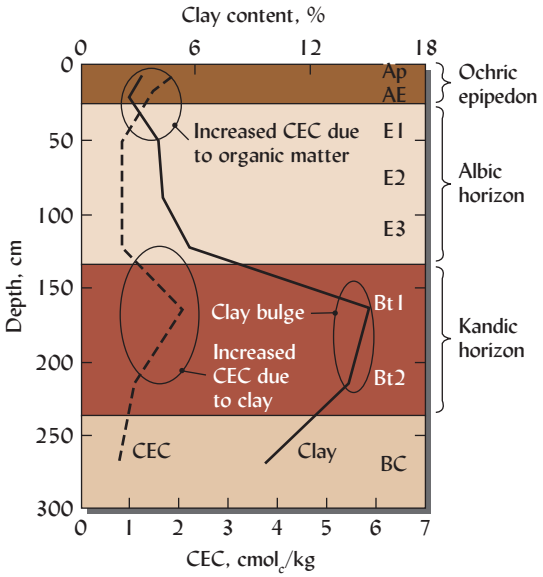

Figure 3.6 *Vertical variation in clay content and cation exchange capacity (CEC) in a soil with thick albic and kandic horizons (E1-E2-E3 and Bt1-Bt2, respectively). Note the well-expressed "clay bulge" that marks the kandic horizon. Similar clay enrichment (plus clay skins or other visual evidence of clay illuviation) characterizes an argillic horizon. This is a kandic rather than an argillic horizon because there was no visible evidence of clay illuviation and because the accumulated clay is of low-activity types, meaning the CEC of the clay is less than 16 cmol$_c$/kg of clay. Note that the CEC of the clay = CEC of the soil × 100 ÷ percent clay in the soil. The sharp increase in clay at the upper boundary of the kandic horizon, the considerable thickness (more than 100 cm) of the clay-rich layer, and the low CEC per kg of clay are all indications that this is a very old, highly mature soil. It formed under humid, subtropical conditions in sandy sediments in the upper coastal plain of Georgia, USA. It is classified in the Kandiudults great group in* Soil Taxonomy. (Data from Shaw et al., 2000)

($CaSO_4$ $2H_2O$), and **salic horizons** have an accumulation of soluble salts. These are found mostly in soils of arid and semiarid regions.

In some subsurface diagnostic horizons, the materials are cemented or densely packed, resulting in relatively impermeable layers called *pans* (**duripan**, **fragipan**, and **placic horizons**).[6] These can resist water movement and the penetration of plant roots. Such pans constrain plant growth and may encourage water runoff and erosion because rainwater cannot move readily downward through the soil. Figure 3.4 explains the genesis of these and the other subsurface diagnostic horizons.

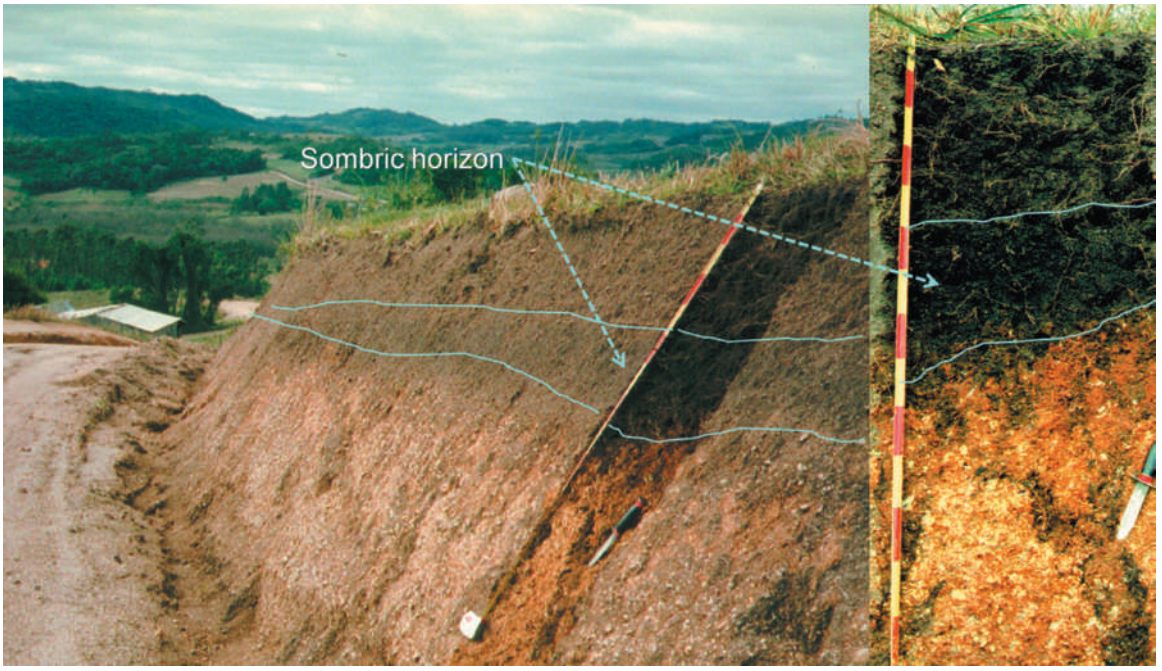

Figure 3.7 *A road cut in mountainous terrain in southern Brazil exposing the profile with a sombric diagnostic subsurface horizon. This dark, humus-rich horizon usually forms in high altitude, humid tropical and subtropical mountains with wet, cool (but not freezing) conditions.* (Photos courtesy of Ray R. Weil)

[6]Well-developed argillic horizons may present such a great and abrupt increase in clay content that water and root movement are severely restricted; such a horizon is commonly referred to by the non-taxonomic term, *claypan*.

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Soil Moisture Regimes (SMRs)

A SMR refers to the presence or absence of either water-saturated conditions (usually groundwater) or plant-available soil water during specified periods in the year in what is termed the *control section* of the soil. The upper boundary of the SMR control section is the depth that 2.5 cm of water will penetrate within 48 hours when added to a dry soil. The lower boundary is the depth that 7.5 cm of water will penetrate. Generally, the control section ranges from 10 to 30 cm for soils high in fine particles (clay) and from 30 to 90 cm for sandy soils. Several moisture regime classes are used to characterize soils.

Aquic. Soil is saturated with water and virtually free of gaseous oxygen for sufficient periods of time for evidence of poor aeration (gleying and mottling) to occur.

Udic. Soil moisture is sufficiently high year-round in most years to meet plant needs. This regime is common for soils in humid climatic regions and characterizes about one-third of the worldwide land area. An extremely wet moisture regime with excess moisture for leaching throughout the year is termed **perudic**.

Ustic. Soil moisture is intermediate between Udic and Aridic regimes—generally winters are relatively dry, but the growing season is characterized by some plant-available moisture between significant periods of drought.

Aridic. The soil is dry for at least half of the growing season and moist for less than 90 consecutive days. This regime is characteristic of arid regions. The term *torric* is used to indicate the same moisture condition in certain soils that are both hot and dry in summer, though they may not be hot in winter.

Xeric. This SMR is found in typical Mediterranean-type climates, with cool, moist winters and warm, dry summers. Like the Ustic regime, it is characterized by having long periods of drought in the summer.

These terms are used to diagnose the SMR and are helpful not only in classifying soils but in suggesting their most sustainable long-term uses.

Soil Temperature Regimes

Soil temperature regimes, such as frigid, mesic, and thermic, are used to classify soils at some of the lower levels in *Soil Taxonomy*. The cryic (Greek *kryos*, very cold) temperature regime distinguishes some higher-level groups. These regimes are based on mean annual soil temperature, mean summer temperature, and the difference between mean summer and winter temperatures, all at 50 cm depth. The specific temperature regimes will be described in the discussion of soil families (Section 3.17).

3.3 CATEGORIES AND NOMENCLATURE OF SOIL TAXONOMY

There are six hierarchical categories of classification in *Soil Taxonomy:* (1) *order*, the highest (broadest) category, (2) *suborder*, (3) *great group*, (4) *subgroup*, (5) *family*, and (6) *series* (the most specific category). The lower categories fit within the higher categories (Figure 3.8). Thus, each order has several suborders, each suborder has several great groups, and so forth. This system may be compared with those used for the classification of plants or animals, as shown in Table 3.2. Just as *Trifolium repens* identifies a specific kind of plant, the Miami series identifies a specific kind of soil.

Nomenclature of Soil Taxonomy

Although unfamiliar at first sight, the nomenclature system has a logical construction and conveys a great deal of information about the nature of the soils named. The system is easy to learn after a bit of study. The nomenclature is used throughout this book, especially to identify the kinds of soils shown in illustrations. When reading, if you make a conscious effort to identify the parts of each soil class mentioned in the text and figure captions and recognize the level of category indicated, the system will become second nature.

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Table 3.2
COMPARISON OF THE CLASSIFICATION OF A COMMON CULTIVATED PLANT, WHITE CLOVER (*TRIFOLIUM REPENS*), AND A SOIL, MIAMI SERIES

Plant Classification			Soil Classification	
Phylum	Pterophyta	Increase specificity ↓	Order	Alfisols
Class	Angiospermae		Suborder	Udalfs
Subclass	Dicotyledoneae		Great Group	Hapludalfs
Order	Rosales		Subgroup	Oxyaquic Hapludalfs
Family	Leguminosae		Family	Fine loamy, mixed, mesic, active
Genus	*Trifolium*		Series	Miami
Species	*repens*		Phase[a]	Miami silt loam

[a]Technically not a category in *Soil Taxonomy* but used in field surveying. *Silt loam* refers to the texture of the A horizon.

The names of the classification units are combinations of syllables, most of which are derived from Latin or Greek, and are root words in several modern languages. Since each part of a soil name conveys a concept of soil character or genesis, the name automatically describes the general kind of soil being classified. For example, soils of the order **Aridisols** (from the Latin *aridus*, dry, and *solum*, soil) are characteristically dry soils in arid regions. Those of the order **Inceptisols** (from the Latin *inceptum*, beginning, and *solum*, soil) are soils with only the beginnings or inception of profile development. Thus, the names of orders are combinations of (1) formative elements, which generally define the characteristics of the soils, and (2) the ending *sols.*

The names of suborders automatically identify the order of which they are a part. For example, soils of the suborder **Aquolls** are the wetter soils (from the Latin *aqua*, water) of the Mollisols order. Likewise, the name of the great group identifies the suborder and order of which it is a part. **Argiaquolls** are Aquolls with clay or argillic (Latin *argilla*, white clay) horizons. In the following illustration, note that the three letters *oll* identify each of the lower categories as being in the M*oll*isols order.

M*oll*isols	Order
Aqu*oll*s	Suborder
Argiaqu*oll*s	Great group
Typic Argiaqu*oll*s	Subgroup

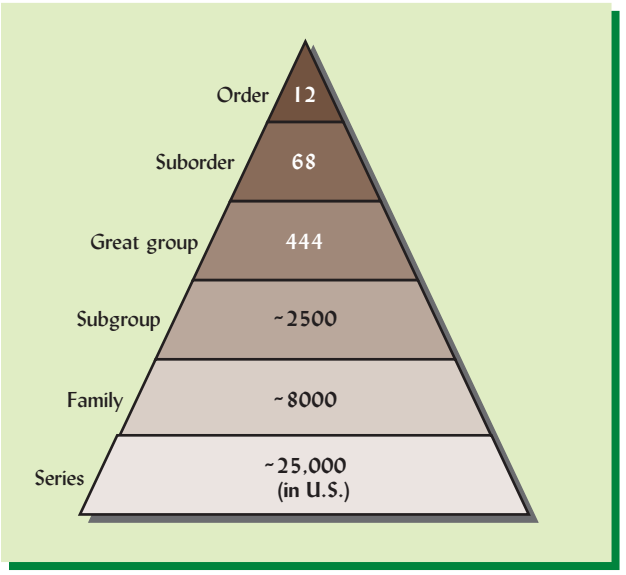

Figure 3.8 *The categories of* Soil Taxonomy *and approximate number of units in each category.*

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If one is given only the subgroup name, the great group, suborder, and order to which the soil belongs are automatically known.

Family names in general identify subsets of the subgroup that are similar in texture, mineral composition, and mean soil temperature at a depth of 50 cm. Thus the name *fine, mixed, mesic, active Typic Argiaquolls* identifies a family in the Typic Argiaquolls subgroup with a fine texture, mixed clay mineral content, mesic (8–15 °C) mean soil temperature, and clays active in cation exchange.

Soil series are generally named after a geographic feature (town, river, etc.) near where they were first recognized. Thus, names such as *Cecil*, *Harare*, *Miami*, *Norfolk*, and *Ontario* identify soil series first described near the town or geographic feature named. Many thousands of soil series have been classified worldwide.

In detailed field soil surveying, soil series are sometimes further differentiated on the basis of surface soil texture, degree of erosion, slope, or other characteristics. These practical subunits are called soil ***phases***. Names such as *Cecil clay loam and eroded phase* are used to identify such phases. Note, however, that soil phases, practical as they may be in local situations, are *not* a category in the *Soil Taxonomy* system.

With this brief explanation of the nomenclature of *Soil Taxonomy*, we will now consider the general nature of soils in the 12 orders.

3.4 SOIL ORDERS

Each of the world's soils is assigned to one of 12 **orders**, largely on the basis of soil properties that reflect a major course of development, with considerable emphasis placed on the presence or absence of major diagnostic horizons (Table 3.3). As an example, many soils that developed under grassland vegetation have the same general sequence of horizons and are characterized

Table 3.3
NAMES OF SOIL ORDERS IN *SOIL TAXONOMY* WITH THEIR DERIVATION AND MAJOR CHARACTERISTICS
The bold letters in the order names indicate the formative element used as the ending for suborders and lower taxa within that order.

Name	Formative Element	Derivation	Pronunciation	Major Characteristics
Alfisols	alf	Nonsense symbol	Ped**alf**er	Argillic, natric, or kandic horizon; high-to-medium base saturation
Andisols	and	Jap. *ando*, black soil	**And**esite	From volcanic ejecta, dominated by allophane or Al-humic complexes
Ar**id**isols	id	L. *aridus*, dry	Ar**id**	Dry soil, ochric epipedon, sometimes argillic or natric horizon
Entisols	ent	Nonsense symbol	Rec**ent**	Little profile development, ochric epipedon common
Ge**l**isols	el	Gk. *gelid*, very cold	J**el**ly	Permafrost, often with cryoturbation (frost churning)
Hi**st**osols	ist	Gk. *histos*, tissue	Hi**st**ology	Peat or bog; >20% organic matter
Inc**ept**isols	ept	L. *inceptum*, beginning	Inc**ept**ion	Embryonic soils with few diagnostic features, ochric or umbric epipedon, cambic horizon
M**oll**isols	oll	L. *mollis*, soft	M**oll**ify	Mollic epipedon, high base saturation, dark soils, some with argillic or natric horizons
Oxisols	ox	Fr. *oxide*, oxide	**Ox**ide	Oxic horizon, no argillic horizon, highly weathered
Sp**od**osols	od	Gk. *spodos*, wood ash	P**od**zol; odd	Spodic horizon commonly with iron, aluminum oxides and humus accumulation
Ultisols	ult	L. *ultimus*, last	**Ult**imate	Argillic or kandic horizon, low base saturation
V**ert**isols	ert	L. *verto*, turn	Inv**ert**	High in swelling clays; deep cracks when soil is dry

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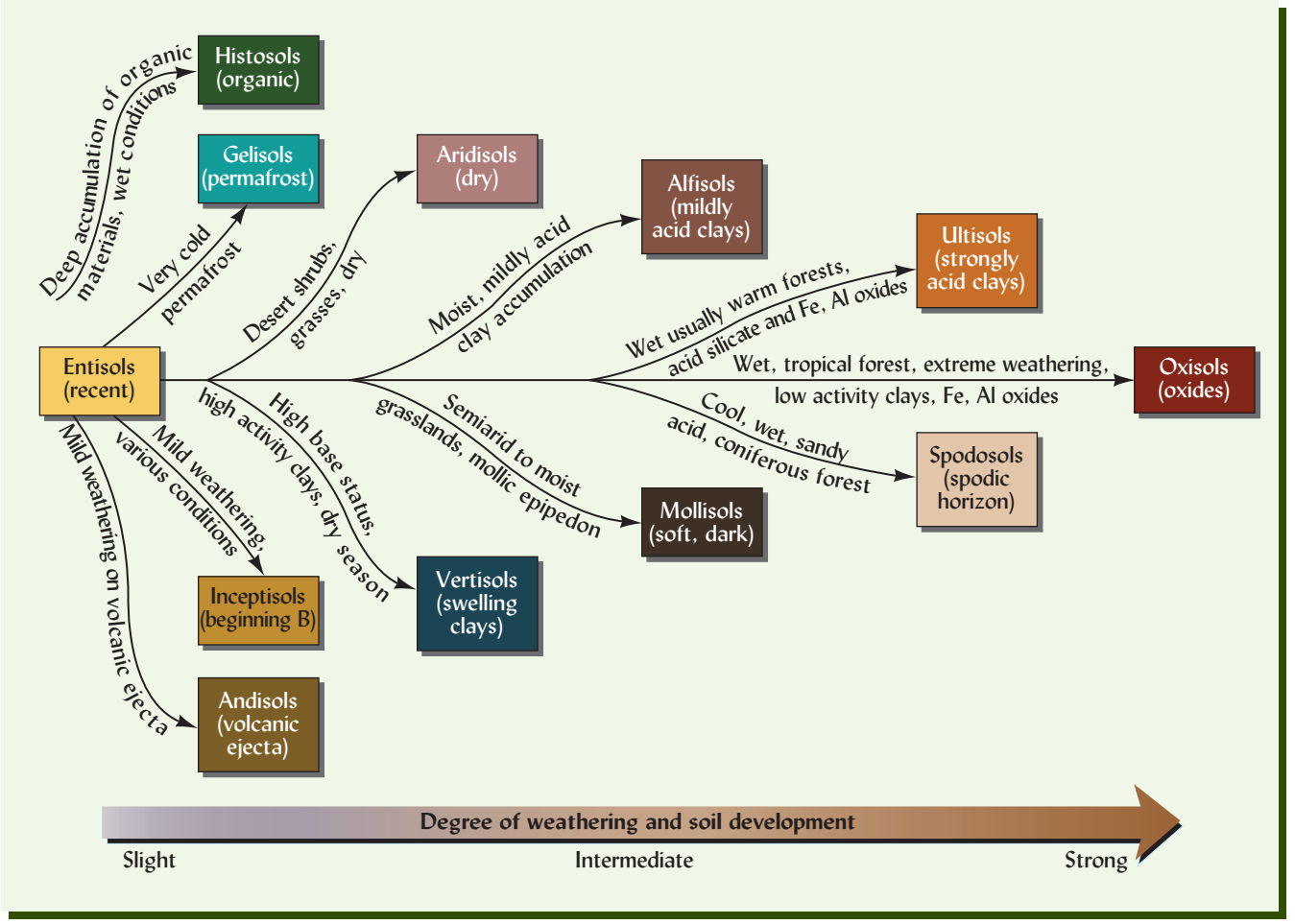

Figure 3.9 *Diagram showing general degree of weathering and soil development in the different soil orders classified in* Soil Taxonomy. *Also shown are the general climatic and vegetative conditions under which soils in each order are formed.* [Diagram courtesy of Brady and Weil. For more on environmental factors influencing the formation of soil orders, see Lin (2011)]

by a mollic epipedon—a thick, dark, surface horizon that is high in nonacid cations. Because of the properties they have in common, these soils are included in the same order: Mollisols. The names and major characteristics of each soil order are shown in Table 3.3. Note that all order names have common ending, sols (from the Latin *solum*, soil).

The general conditions that promote the formation of soils in the different orders are shown in Figure 3.9. From soil profile characteristics, soil scientists can ascertain the relative degree of soil development in the different orders, as shown in this figure. Note that soils with essentially no profile layering (Entisols) have the least development, whereas the deeply weathered soils of the humid tropics (Oxisols and Ultisols) show the greatest soil development. The effect of climate (temperature and moisture) and of vegetation (forests or grasslands) on the kinds of soils that develop is also indicated in Figure 3.9. Study Table 3.3 and Figure 3.9 to better understand the relationship between soil properties and the terminology used in *Soil Taxonomy*.

To some degree, most of the soil orders occur in climatic regions that can be described by moisture and temperature regimes. Figure 3.10 illustrates some of the relationships among the soil orders with regard to these climatic factors. While only the Gelisols and Aridisols orders are defined directly in relation to climate, Figure 3.10 indicates that orders with the most highly weathered soils tend to be associated with the warmer and wetter climates. A general world map of the 12 soil orders is printed in color on the front endpaper. A more detailed color-coded soil map for the United States can be found on the back endpaper

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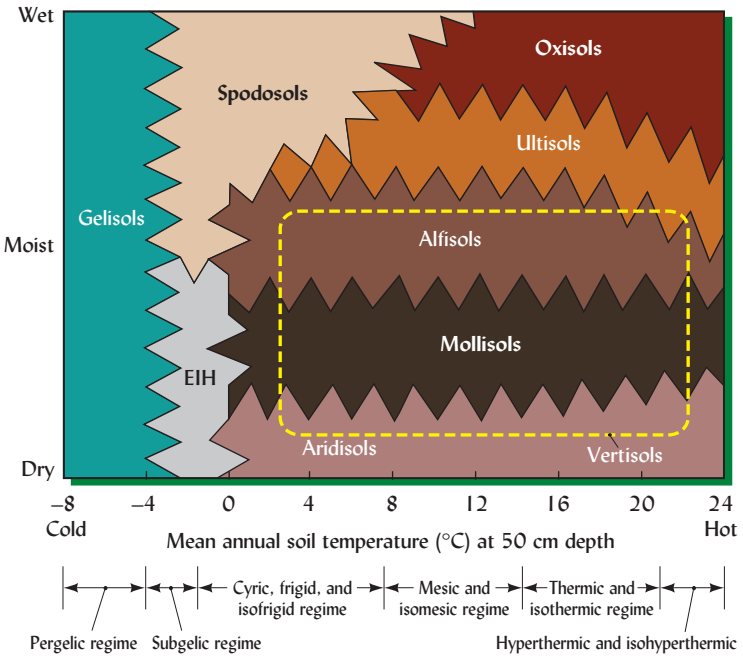

Figure 3.10 *Diagram showing the general soil moisture and soil temperature regimes that characterize the most extensive soils in each of eight soil orders. Soils of the other four orders (Andisols, Entisols, Inceptisols, and Histosols) may be found under any of the soil moisture and temperature conditions (including the area marked EIH). Major areas of Vertisols are found only where clayey materials are in abundance and are most extensive where the soil moisture and temperature conditions approximate those shown inside the box with broken lines. Note that these relationships are only approximate and that less extensive areas of soils in each order may be found outside the indicated ranges. For example, some Ultisols (Ustults) and Oxisols (Ustox) have soil moisture levels for at least part of the year that are much lower than this graph would indicate. (The terms used at the bottom to describe the soil temperature regimes are those used in helping to identify soil families.)*

of this book. A typical profile and global distribution map for each soil order are shown at the beginning of Sections 3.5–3.16. In studying these maps, try to confirm that the distribution of the soil orders is in accordance with what you know about the climate in various regions of the world.

Although a detailed description of all the lower levels of soil categories is far beyond the scope of this (or any other) book, a general knowledge of the 12 soil orders is essential for understanding the nature and function of soils in different environments. The simplified key given in Figure 3.11 helps illustrate how *Soil Taxonomy* can be used to key out the order of any soil based on observable and measurable properties of the soil profile. Because certain diagnostic properties take precedence over others, the key must always be used starting at the top, and working down. It will be useful to review this key after reading about the general characteristics, nature, and occurrence of each soil order.

We will now consider each of the soil orders, beginning with those characterized by little profile development and progressing to those with the most highly weathered profiles (as represented from left to right in Figure 3.9).

3.5 ENTISOLS (RECENT: LITTLE IF ANY PROFILE DEVELOPMENT)

Weakly developed mineral soils without natural genetic (subsurface) horizons or with only the beginnings of such horizons (Figure 3.12) belong to the Entisols order. Most have an ochric epipedon and a few have human-made anthropic or agric epipedons. Some have albic subsurface horizons. Soil productivity ranges from very high for certain Entisols formed in recent alluvium to very low for those forming in shifting sand or on steep rocky slopes.

This is an extremely diverse group of soils with little in common, other than the lack of evidence for all but the earliest stages of soil formation. Entisols are either young in years or their parent materials have not reacted to soil-forming factors. On such parent materials as fresh lava flows or recent alluvium (Fluvents), there has been too little time for much soil formation. In extremely dry areas, scarcity of water and vegetation may inhibit soil formation. Likewise, frequent saturation or inundation with water (Aquents, Wassents) may delay soil formation. Some Entisols occur on steep slopes, where the rates of erosion may exceed the rates of soil formation, preventing horizon development. Others occur on urbanized areas

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Figure 3.11 *A simplified key to the 12 soil orders in* Soil Taxonomy. *In using the key, always begin at the top. Note how diagnostic horizons and other profile features are used to distinguish each soil order from the remaining orders. Entisols, having no such special diagnostic features, key out last. Also note that the sequence of soil orders in this key bears no relationship to the degree of profile development and adjacent soil orders may not be more similar than nonadjacent ones. See Section 3.2 for explanations of the diagnostic horizons.*

and construction sites where bulldozers have destroyed or mixed together the soil original horizons, causing the existing soils to become Entisols as the horizon formation process must start anew.

Distribution and Use

Globally, Entisols are found under a wide variety of environmental conditions (Figure 3.12). Entisols developed on alluvial floodplains are among the world's most productive soils. Such soils, with their level topography, proximity to water for irrigation, and periodic nutrient replenishment by floodwater sediments, have supported the development of many

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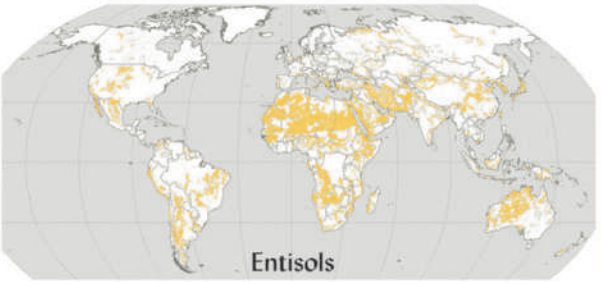

16.3% of global ice-free land

Suborders are:

Aquents (wet)
Fluvents (alluvial deposits)
Orthents (typical)
Psamments (sandy)
Wassents (under water)

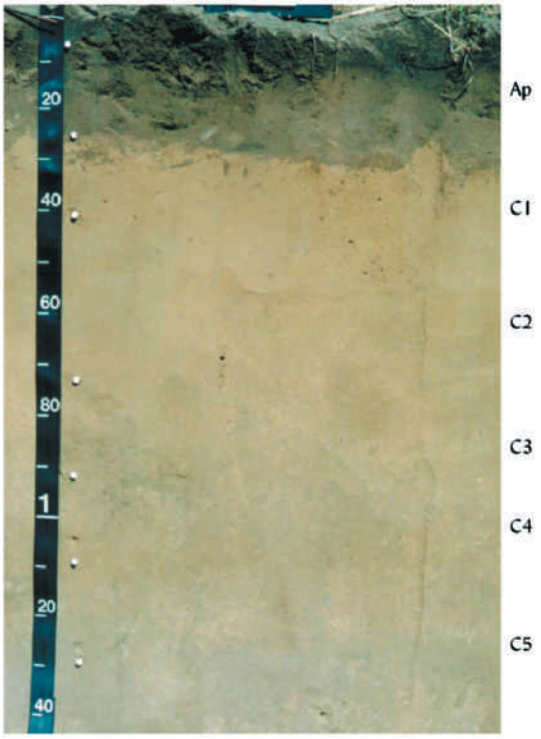

Figure 3.12 *Entisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Udispamment on a flood plain in North Carolina, USA* (Photo courtesy of Ray R. Weil)

major civilizations. However, the productivity of most Entisols is restricted by inadequate soil depth, clay content, or water availability. For example, in rocky and mountainous regions, medium-textured Entisols (Orthents, e.g., Figure 3.13) are commonly too shallow to support high plant productivity, especially in dry regions. Sandy Entisols (Psamments; Figure 3.12) are found in parts of the Sahara desert, southern Africa, central Australia, northwest Nebraska, USA and the southeastern U.S. coastal plain. Psamments in the humid southern United States are successfully used for citrus, vegetable, and peanut production. Poorly drained and seasonally flooded Entisols (Aquents) occur in major river valleys and wetlands, whereas subaqueous Entisols (Wassents) are important for supporting submerged aquatic vegetation in shallow estuaries and bays.

Figure 3.13 *Shallow Entisols (Udorthents) on a steep rocky slope support moderately productive forest in a humid temperate climate.* (Photo courtesy of Ray R. Weil)

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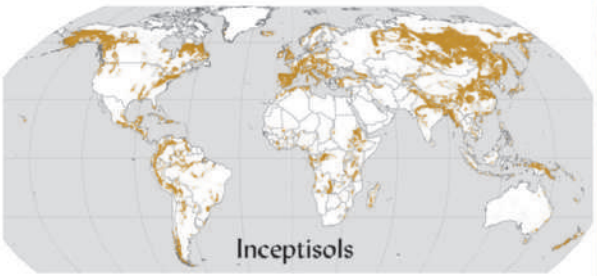
3.6 INCEPTISOLS (FEW DIAGNOSTIC FEATURES: INCEPTION OF B HORIZON)

In Inceptisols the beginning or *inception* of profile development is evident, and some diagnostic features are present (Figure 3.14). However, the well-defined profile characteristics of soils thought to be more mature have not yet developed. For example, a cambic horizon showing some color or structural change is common in Inceptisols, but a more mature illuvial B horizon such as an argillic cannot be present. Other subsurface diagnostic horizons that may be present in Inceptisols include duripans, fragipans, and calcic, gypsic, and sulfuric horizons. The epipedon in most Inceptisols is an ochric, although a plaggen or weakly expressed mollic or umbric epipedon may be present. Inceptisols show more significant profile development than Entisols but are defined to exclude soils with diagnostic horizons or properties that characterize certain other soil orders. Thus, soils with only slight profile development occurring in arid regions or containing permafrost or andic properties are excluded from the Inceptisols. They fall, instead, in the soil orders Aridisols, Gelisols, or Andisols, as discussed in later sections.

Distribution and Use

As with Entisols, Inceptisols are found in most climatic and physiographic conditions. They are often prominent in mountainous areas (Figure 3.15). They are also probably the most important soil order in the lowland rice-growing areas of Asia.

Inceptisols are found in each of the continents (see front papers). Inceptisols of humid regions, called *Udepts*, often have only thin, surface horizons (ochric epipedons). Udepts, along with Xerepts (Inceptisols in xeric climates), dominate an area extending from southern Spain through central France to Germany and are present as well in Chile, North Africa, eastern China, and western Siberia. Udepts are also common in the eastern US mountains from southern New York through the Carolinas. Wet Inceptisols or Aquepts are found in areas along the Amazon and Ganges rivers. The natural productivity of Inceptisols is highly variable.



9.9% of global ice-free land

Suborders are:

- Aquepts (wet)
- Cryepts (very cold)
- Gelepts (permafrost)
- Udepts (humid climate)
- Ustepts (semiarid)
- Xerepts (dry summers, wet winters)

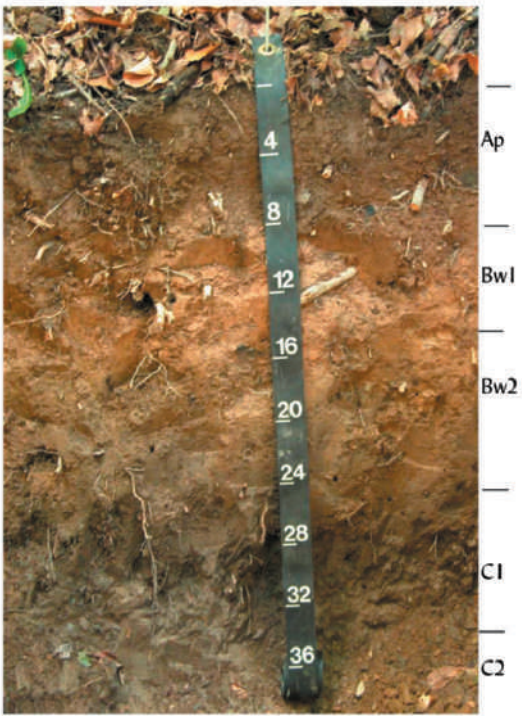


Figure 3.14 *Inceptisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Eutrodept from Vermont, USA.* (Photo courtesy of Ray R. Weil)

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Figure 3.15 *Inceptisols, like the Humic Dystrudept shown here, are common in mountainous terrain where steep slopes retard profile development, forming a cambic diagnostic horizon (Bw), which features a change in color and structure but no illuvial accumulation of clay. Wayah series, Blue Ridge Mountains in North Carolina, USA. Scale in centimeters.* (Photos courtesy of Ray R. Weil)

3.7 ANDISOLS (VOLCANIC ASH SOILS)

Andisols are usually formed on volcanic ash and cinders deposited in recent geological times. They are commonly found near the volcano source or in areas downwind from the volcano, where a sufficiently thick layer of ash has been deposited during eruptions. Andisols have not had time to become highly weathered. The principal soil-forming process has been the rapid weathering (transformation) of volcanic ash to produce amorphous or poorly crystallized silicate minerals such as ***allophane*** and ***imogolite*** and the iron oxy-hydroxide, ***ferrihydrite***. Some Andisols have a melanic epipedon, a surface diagnostic horizon that has a high organic matter content and dark color (Figures 13.16–13.17). The accumulation of organic matter is quite rapid due largely to its protection in aluminum–humus complexes. Little downward translocation of the colloids, or other profile development, has taken place. Like the Entisols and Inceptisols, Andisols are young soils, usually having developed for only 5000–10,000 years.

Unlike the previous two orders of immature soils, Andisols have a unique set of ***andic properties*** in at least 35 cm of the upper 60 cm of soil due to common types of parent materials. Materials with andic properties are characterized by a high content of volcanic glass and/or a high content of amorphous or poorly crystalline iron and aluminum minerals. The combination of these minerals and the high organic matter results in light, fluffy soils that are easily tilled, yet have a high water-holding capacity and resist erosion by water. They are mostly found in regions where rainfall keeps them from being susceptible to erosion by wind. Andisols are usually of high natural fertility, except that phosphorus (P) availability is severely limited by the extremely high P retention capacity of the andic materials (see Section 14.8). Fortunately, proper management of plant residues and fertilizers can usually overcome this difficulty.

Distribution and Use

Andisols are found in areas where significant depths of volcanic ash and other ejecta have accumulated (Figure 3.16). Globally, they make up less than 1% of the soil area. Andisols

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0.7% of global ice-free land

Suborders are:

Aquands (wet)
Cryands (cold)
Gelands (very cold)
Torrands (hot, dry)
Udands (humid)
Ustands (moist/dry)
Vitrands (volcanic glass)
Xerands (dry summers, moist winters)

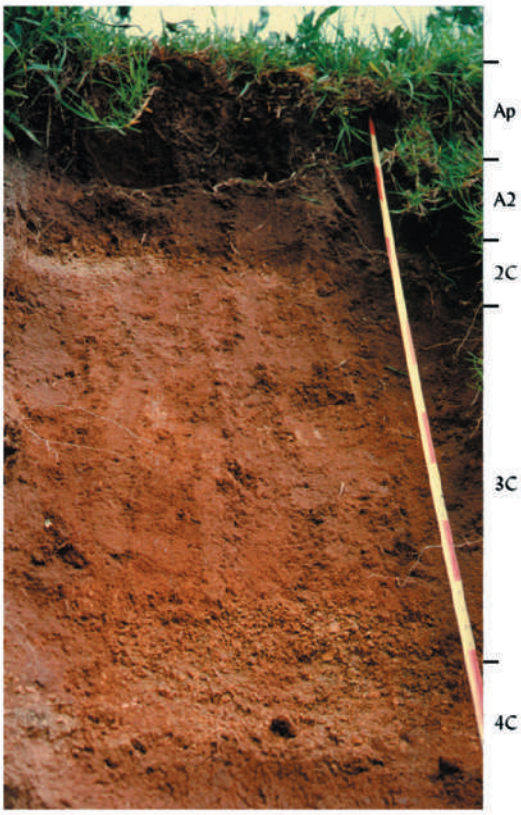

Figure 3.16 *Andisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Melanudand from western Tanzania. Scale in decimeters.* (Ray R. Weil)

having a udic (humid) moisture regime (Udands) and the somewhat drier Ustands are both used intensively for agriculture. In the Pacific Rim and African Rift areas they are important and productive soils that support intensive agriculture, especially where they occur at high-elevations. Andisols are found to a minor extent in cold climates (Cryands) in Canada and Russia, and in hot, dry climates (Torrands) in Mexico and Syria. In the United States, significant areas of Andisols occur in Washington, Idaho, Montana, and Oregon. Very recent eruptions are giving rise to Vitrands that still have much volcanic glass and lower water-holding capacities.

Figure 3.17 *Two Andisols (in Ethiopia,* left, *and Washington State, USA,* right) *illustrating whitish ash layers laid down by repeated volcanic eruptions and black, buried A horizons formed during sequential periods of soil development between eruptions.* (Photos courtesy of Ray R. Weil)

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3.8 GELISOLS (PERMAFROST AND FROST CHURNING)

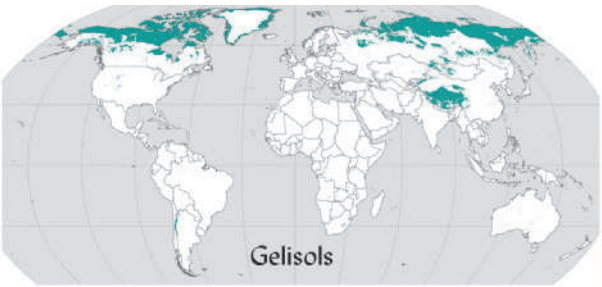
Gelisols are young soils with little profile development. Cold temperatures and frozen conditions for much of the year slow the process of soil formation. The principal defining feature of these soils is the presence of a ***permafrost*** layer (see Figures 3.18–3.19). Permafrost is a layer of material that remains at temperatures below 0 °C for more than two consecutive years. It may be a hard, ice-cemented layer of soil material (e.g., designated Cfm in profile descriptions), or, if dry, it may be uncemented (e.g., designated Cff). In Gelisols, the permafrost layer lies within 100 cm of the soil surface, unless ***cryoturbation*** is evident within the upper 100 cm, in which case the permafrost may begin as deep as 200 cm from the soil surface.

Cryoturbation is the physical disturbance of soil materials caused by the formation of ice wedges and by the expansion and contraction of water as it freezes and thaws. This *frost-churning* action moves the soil material so as to orient rock fragments along the lines of force and to form broken, convoluted horizons (e.g., designated Cjj) at the top of the permafrost. The frost churning also may form patterns on the ground surface, such as hummocks and ice-rich polygons that may be several meters across. In some cases, rocks forced to the surface form rings or netlike patterns.

Gelisols showing evidence of cryoturbation are called *Turbels.* Other Gelisols, often found in wet environments, have developed in accumulations of mainly organic materials, making them ***Histels*** (Greek *histos*, tissue; Figure 3.19). Most of the soil-forming processes that occur take place above the permafrost in the ***active layer*** that thaws every year or two. Various types of diagnostic horizons may have developed in different Gelisols, including mollic, histic, umbric, calcic, and, occasionally, argillic horizons.

Distribution and Use

Gelisols are most extensive in Northern Russia, Canada, and Alaska. Blanketed under snow and ice for much of the year, most Gelisols support tundra vegetation of lichens, grasses, and low shrubs that grow during the brief summers. Large areas of Gelisols consist of bogs, some literally



8.6% of global ice-free land

Suborders are:
Histels (organic)
Orthels (no special features)
Turbels (cryoturbation)

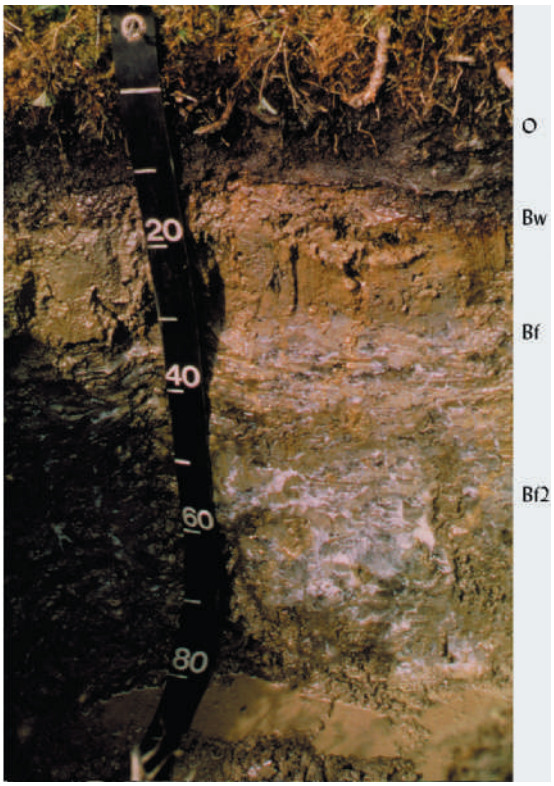


Figure 3.18 *Gelisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Aquaturbel from Alaska. Permafrost is seen below 32 cm in this profile.* (Photo courtesy of Chien-lu Ping, University of Alaska, Fairbanks)

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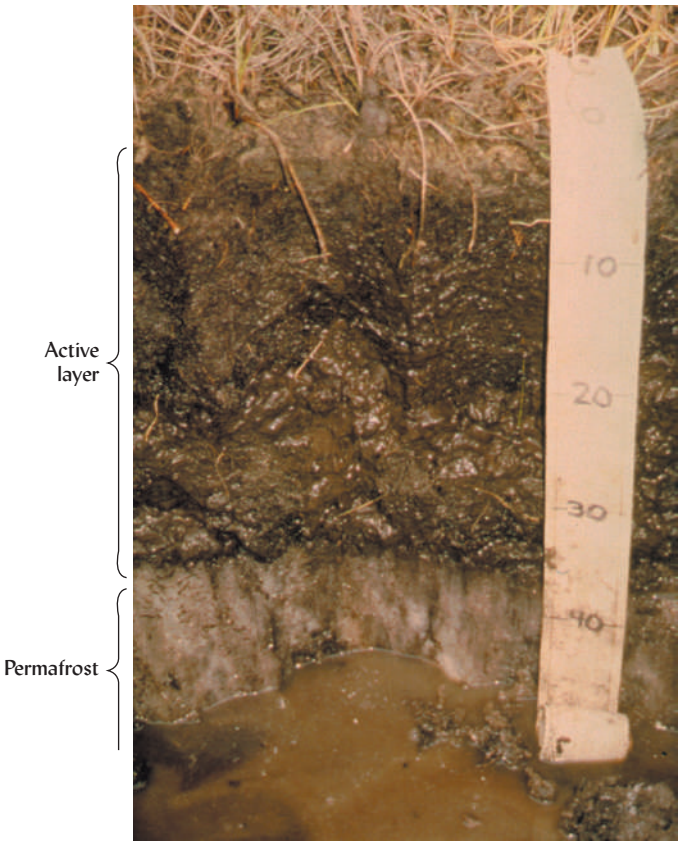

Figure 3.19 *Gelisols in Alaska.* (Left) *The soil is in the suborder Histels and has a histic epipedon and permafrost. This soil was photographed in Alaska in July. Scale in cm.* (Right) *Melting of the permafrost under this section of the Alaska Highway caused the soil to lose all bearing strength and collapse. Scale in cm.* (*Left* photo courtesy of Chien-Lu Ping/University of Alaska, Fairbanks; *right* photo courtesy of John Moore, USDA/NRCS)

floating on layers of frozen or unfrozen water. Millions of caribou, reindeer, and musk ox survive on this vegetation during the summer, then migrate to the boreal forests during the coldest seasons. The many bogs and pools serve as nesting sites for migratory birds, which feed on the thick clouds of biting flies and mosquitoes. Few humans live in these inhospitable environments.

Gelisols are rarely used for agriculture. Plant productivity is low because of the extremely short potential growing season in the far northern latitudes, the low levels of solar radiation (except during the fleeting summer), and the waterlogged condition of many Gelisols in which permafrost inhibits internal drainage during the summer thaw (Figure 3.19).

If the vegetation or insulating surface peat layer on Gelisols is disturbed (as by cultivation, forest fires or construction activities), the permafrost layer may melt. The permafrost in the southern part of the Gelisols region is only 1 or 2 °C below freezing, so even small changes can cause melting. Unless the soil is mainly gravel, the melting is likely to cause the soil to completely lose its bearing strength and collapse. This presents many serious engineering difficulties (see Figure 3.19, *right*). Houses built directly on Gelisols may sink into the ground as the heat from inside the building penetrates the soil and melts the permafrost. Oil pipelines must be constructed on stilts, rather than buried as the heat from the flowing oil would melt the permafrost, causing the pipes to sag and rupture.

Permafrost melting in Gelisols is an early symptom of global climate change caused by greenhouse gas emissions (see Section 12.9). Unfortunately, the melting of permafrost and deepening of the active layer in Gelisols appears to be accelerating this trend as the enormous pools of organic carbon once locked away in the permafrost become exposed to decay, thus releasing yet more greenhouse gases to the atmosphere.

3.9 HISTOSOLS (ORGANIC SOILS WITHOUT PERMAFROST)

Histosols are soils that have undergone little profile development because of the anaerobic environment in which they form. The main process of soil formation evident in Histosols is the accumulation of partially decomposed organic parent material without permafrost (which

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1.2% of global ice-free land

Suborders are:

Fibrists (fibers of plants obvious)
Folists (leaf mat accumulations)
Hemists (fibers partly decomposed)
Saprists (fibers not recognizable)
Wassists (underwater most of the time)

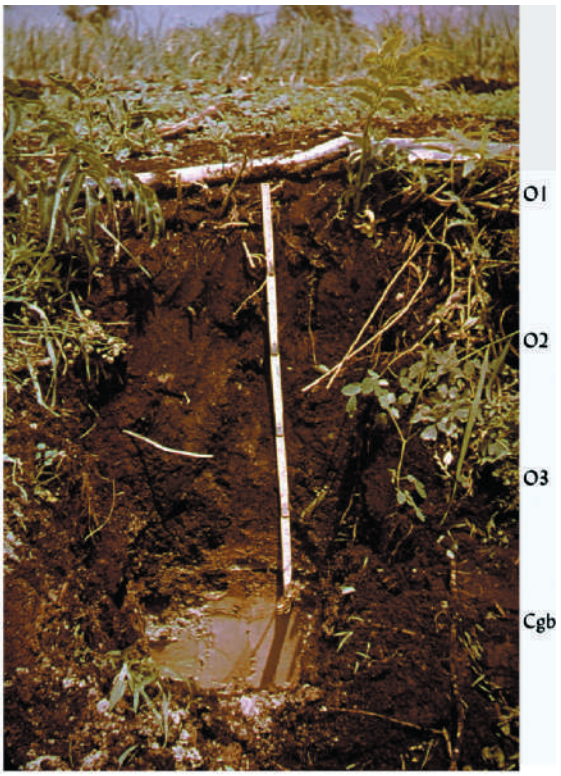

Figure 3.20 *Histosols soil order—global distribution, land area, suborders, and a representative profile, a Limnic Haplosaprist from southern Michigan, USA. A buried mineral soil can be seen at the bottom of the scale (which is marked in 30 cm increments).* (Photo courtesy of USDA/NRCS)

would cause the soil to be classified in the Histels suborder of Gelisols). Histosols consist of one or more thick layers of *organic soil material* (see footnote 6, page 109). Generally, Histosols have organic soil materials in more than half of the upper 80 cm of soil (Figure 3.20) or in two-thirds of the soil overlying shallow rock.

Organic deposits accumulate in marshes, bogs, and swamps, which are habitats for hydrophilic (water-loving plants) such as sedges, reeds, mosses, shrubs, and even some trees. Generation after generation, the residues of these plants sink into the water, where low oxygen conditions inhibit their decomposition and, consequently, act as a partial preservative (see Figure 2.22).

The organic matter in Histosols ranges from peat to muck. *Peat* is comprised of the brownish, only partially decomposed, fibrous remains of plant tissues (see Figures 3.21 and 3.22). Some of these soils are mined and sold as peat, a material widely used in containerized plant production (see Box 12.4). Peat deposits are also used for fuel in some countries, especially in Russia, where several power stations are fueled by this material. *Muck*, on the other hand, is a smooth colloidal black material in which decomposition is much more complete (Figure 3.23). Muck is like black ooze when wet and powdery when dry.

While not all wetlands contain Histosols, all Histosols (except Folists) occur in wetland environments. They can form in almost any moist climate in which plants can grow, from equatorial to arctic regions, but they are most prevalent in cold climates, up to the limit of permafrost. Horizons are differentiated by the type of vegetation contributing the residues, rather than by translocations and accumulations within the profile.

Whether artificially drained for cultivation or left in their natural water-saturated state, Histosols possess unique properties resulting from their high organic matter contents. Histosols are generally black to dark brown in color and extremely lightweight (0.15–0.4 Mg/m^3) when dry, being only about 10–20% as dense as most mineral soils. Histosols possess very high capacities to hold both water (up to 400% of soil dry weight) and nutrient cations (see Sections 5.9 and 8.9). The water- and cation-holding capacities are much higher than those of even clay-rich mineral soils on a weight basis, but similar to those of mineral soils rich in 2:1 silicate clays when considered on a volume basis (water or cations held per liter of soil).

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Figure 3.21 *A highland bog landscape in northern Scotland with Fibrist soil profile.* (Photos courtesy of Ray R. Weil)

Figure 3.22 *A tidal marsh Histosol. The inset shows the* fibric (*peaty*) *organic material that contains recognizable roots and rhizomes of marsh grasses that died perhaps centuries ago, the anaerobic conditions having preserved the tissues from extensive decay. The soil core* (*held horizontally for the photograph*) *gives some idea of the soil profile, the surface layer being at the right and the deepest layer at the left. The water level is usually at or possibly above the soil surface.* (Photos courtesy of Ray R. Weil)

Distribution and Use

Even though they cover only about 1% of the world's land area, Histosols, especially **peat lands**, comprise significant areas in cold, wet regions of Finland, Russia, Iceland, Ireland, Scotland, Alaska, and Canada. Ecologically important areas of Histosols in the United States include glaciated areas in Wisconsin, Minnesota, New York, and Michigan, tule-reed beds of California, the Everglades of Florida, the bayous of Louisiana, and the tidal

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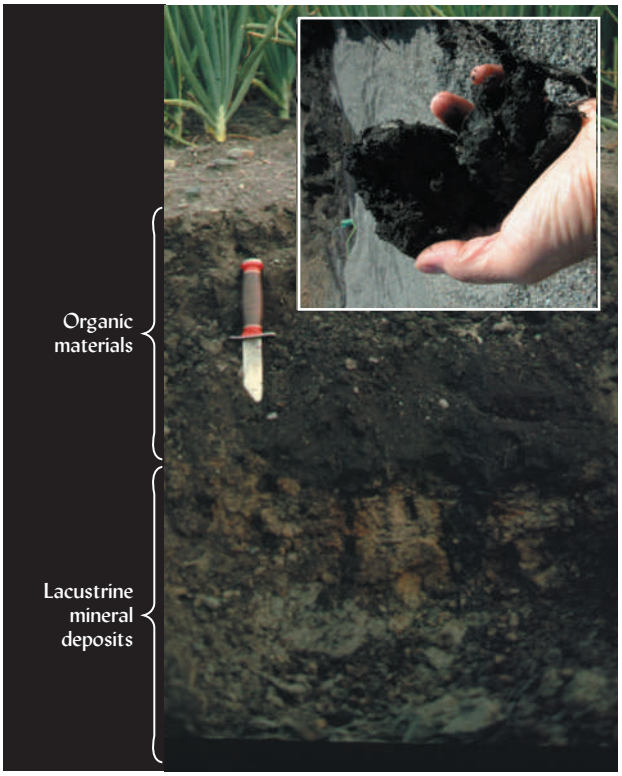

Figure 3.23 *A drained Histosol on which leeks are being produced in New York State. The organic soil rests on old lake-bottom (lacustrine) mineral sediment. The organic material is mucky (see insert), placing this soil in the Saprist suborder. The thickness of this Histosol has been much reduced by subsidence during the nearly 100 years of drainage and cultivation. The surface of this black soil appears light-colored because it was dry when photographed.* (Photos courtesy of Ray R. Weil)

marshes of the mid-Atlantic states (Figure 3.22). Some Histosols (Wassists) occur in shallow lagoons, bays, and lakes and are completely submerged under water all or most of the time.

Because the ecological roles of natural wetland environments have not always been appreciated (or protected by law), more than 50% of the original wetland area in the lower 48 United States has been drained for agricultural or other uses. Some Histosols make very productive farmlands, but the organic nature of the materials requires liming, fertilization, tillage, and drainage practices quite different from those applied to soils in the other 11 orders.

If other than wetland plants are to be grown, the water table is usually lowered to provide an aerated zone for root growth. This practice, of course, alters the soil environment and causes the organic material to oxidize. In drained Histosols, the land surface is actually lowered by as much as 5 cm of soil per year as a result of compression and oxidation, a process termed **subsidence** (see Figure 3.24). To slow the loss of valuable soil resources and avoid unnecessarily aggravating the global climate change (see Section 12.9), the water table in forested or agricultural Histosols should be kept no lower than is needed to assure adequate root aeration. A more

Figure 3.24 *Soil subsidence due to rapid organic matter decomposition after artificial drainage of Histosols in the Florida Everglades, USA. The house was built at ground level, with the septic tank buried about 1 m below the soil surface. Over a period of about 60 years, more than 1.2 m of the organic soil has "disappeared." The loss has been especially rapid because of Florida's warm climate, but artificial drainage that lowers the water table and continually dries out the upper horizons is an unsustainable practice on any Histosol.* (Photo courtesy of George H. Snyder, Everglades Research and Education Center, Belle Glade, FL)

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sustainable approach would be to grow such wetland crops as rice or cranberries or to allow Histosol areas to revert to their native wetland condition (see Section 7.7).

3.10 ARIDISOLS (DRY SOILS)

Aridisols occupy a larger area globally than any other soil order except Entisols. As the name implies, aridity (scarcity of water) is a major characteristic of these soils such that soil moisture sufficient to support plant growth is present for no longer than 90 consecutive days. The natural vegetation consists mainly of scattered desert shrubs and short bunchgrasses. Soil properties, especially in the surface horizons, may differ substantially between interspersed bare and vegetated areas (see Sections 2.5 and 10.1).

Aridisols are characterized by an ochric epipedon that is generally light in color and low in organic matter (see Figure 3.25). Although there is generally not enough water to leach soluble materials completely out of the profile, the processes of soil formation have brought about a redistribution of these materials, often causing them to accumulate at a lower level in the profile. These soils may have a horizon of accumulation of calcium carbonate (calcic), gypsum (gypsic), soluble salts (salic), or exchangeable sodium (natric). With time and the addition of carbonates from calcareous dust and other sources, a B horizon rich in carbonates may form (*Calcids*). Under certain circumstances, carbonates may cement together the soil particles and coarse fragments in the layer of accumulation, producing hard layers known as ***petrocalcic*** horizons (Figure 3.26). These hard layers act as impediments to plant root growth and also greatly increase the cost of excavations for buildings.

Some Aridisols (the *Argids*) have an argillic horizon, most probably formed under a wetter climate that long ago prevailed in many areas that are deserts today. On steeper land surfaces subject to erosion, argillic horizons do not get a chance to form, and the dominant soils are often *Cambids* (Aridisols with only weakly differentiated cambic subsurface B horizons).

In stony or gravelly soils, erosion may remove all the fine particles from the surface layers, leaving behind a layer of wind-rounded pebbles that is called ***desert pavement*** (see Figure 3.26). The surfaces of rocks, including the pebbles in desert pavement, often have a shiny coating called ***desert varnish*** (Figure 3.27).

1.7% of global ice-free land

Suborders are:
- Argids (clay)
- Calcids (carbonate)
- Cambids (typical)
- Cryids (cold)
- Durids (duripan)
- Gypsids (gypsum)

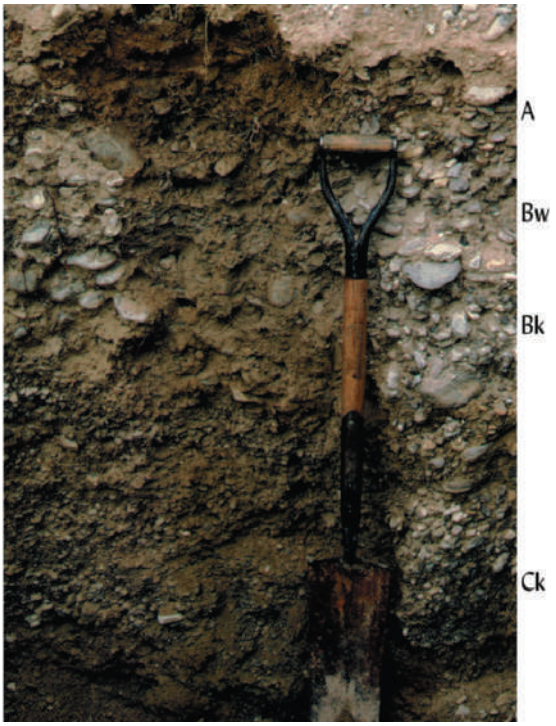

Figure 3.25 *Aridisols soil order—global distribution, land area, suborders, and a representative profile, a skeletal Ustic Haplocalcid from Nevada, USA. Shovel handle is 60 cm long.* (Photo courtesy of Ray R. Weil)

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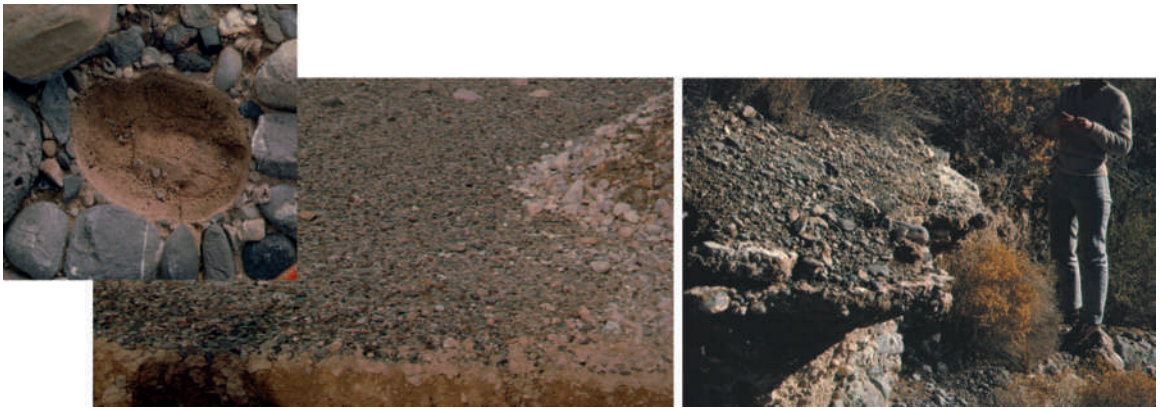

Figure 3.26 *Several features characteristic of some Aridisols.* (Left) *Wind-rounded pebbles have given rise to a desert pavement. The close-up shows a pebble removed to reveal the vesicular pores in the soil underneath. Scale bars = 10 cm.* (Right) *A petrocalcic horizon of cemented calcium carbonate.* (Photo courtesy of Ray R. Weil)

Except where there is groundwater or irrigation, the soil layers are only moist for short periods during the year. These short, moist periods may be sufficient for drought-adapted desert shrubs and annual plants but not for conventional crop production. If groundwater is present near the soil surface, soluble salts may accumulate in the upper horizons to levels that most crop plants cannot tolerate (see Section 10.3).

Distribution and Use

Vast areas of Aridisols are present in the Sahara desert in Africa, the Gobi and Taklamakan deserts in China, and the Turkestan desert of central Asia. Most of the soils of southern and central Australia are Aridisols, as are those of southern Argentina, southwestern Africa, Pakistan, and much of the Middle East. In North America, Aridisols occur mainly in the western United States and northern Mexico.

Without irrigation, Aridisols are not suitable for growing cultivated crops. Some areas are used for low-intensity grazing, especially with sheep or goats, but the production per unit area is low. Poorly managed grazing of Aridisols leads to increased heterogeneity of both soils and vegetation. The animals graze the relatively even cover of palatable grasses, giving a competitive advantage to various shrubs not eaten by the grazing animals. The scattered shrubs compete against the struggling grasses for water and nutrients. The once-grassy areas become increasingly bare, and the soils between the scattered shrubs succumb to erosion by the desert winds and occasional thunderstorms. The desertification of areas of Africa, Asia, and the western United States is evidence of such degradation (Figure 3.28).

Some xerophytic plants, such as a jojoba, have been cultivated on Aridisols to produce various industrial feedstocks such as oil and rubber. Where irrigation water and fertilizers are

Figure 3.27 *Desert varnish is coating thought to be produced by cyanobacteria and algae that extract iron and manganese from the minerals and leave an oxide coating on pebbles and rocks. Ancient desert dwellers have carved a figure in the desert varnish coating on this particular rock in Nevada, USA.* (Photo courtesy of Ray R. Weil)

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Figure 3.28 *The fragile vegetation on Aridisols is easily overgrazed, degrading the vegetation and exposing the soil to rapid erosion by wind and water.* (Photo courtesy of Ray R. Weil)

available, some Aridisols can be made highly productive. Irrigated valleys in arid areas are among the most productive in the world. However, they must be carefully managed to prevent the accumulation of soluble salts (see Section 10.3).

3.11 VERTISOLS (DARK, SWELLING, AND CRACKING CLAYS)[7]

The main soil-forming process affecting Vertisols is the shrinking and swelling of clay as these soils go through periods of drying and wetting. Vertisols have a high content (>30%) of sticky, swelling, and shrinking-type clays to a depth of 1 m or more. Most Vertisols are dark, even blackish in color, to a similar depth (Figure 3.29). However, unlike for most other soils, the dark color of Vertisols is not necessarily indicative of high organic matter content. The organic matter content of dark Vertisols typically ranges from as much as 5 or 6% to as little as 1%.

2.4% of global ice-free land

Suborders are:
- Aquerts (wet)
- Cryerts (cold)
- Torrerts (hot summer, very dry)
- Uderts (humid)
- Usterts (moist/dry)
- Xererts (dry summers, moist winters)

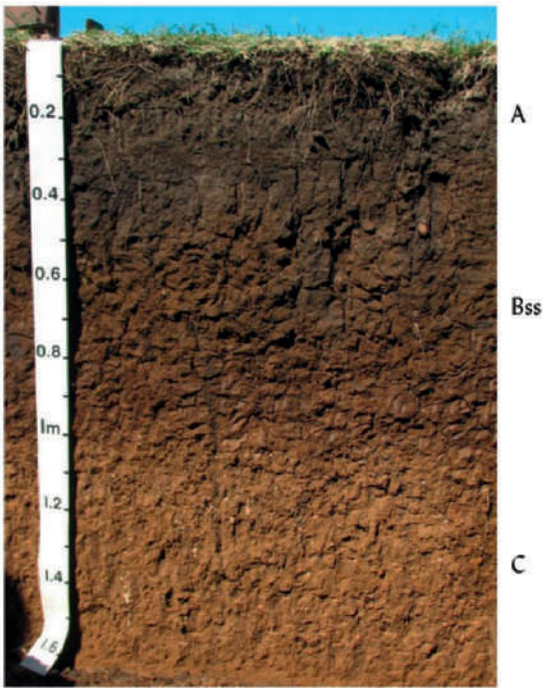

Figure 3.29 *Vertisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Haplustert from Queensland, Australia during the wet season.* (Photo courtesy of Ray R. Weil)

[7]See Coulombe, et al. (1996) for a detailed review of the properties and mode of formation of Vertisols.

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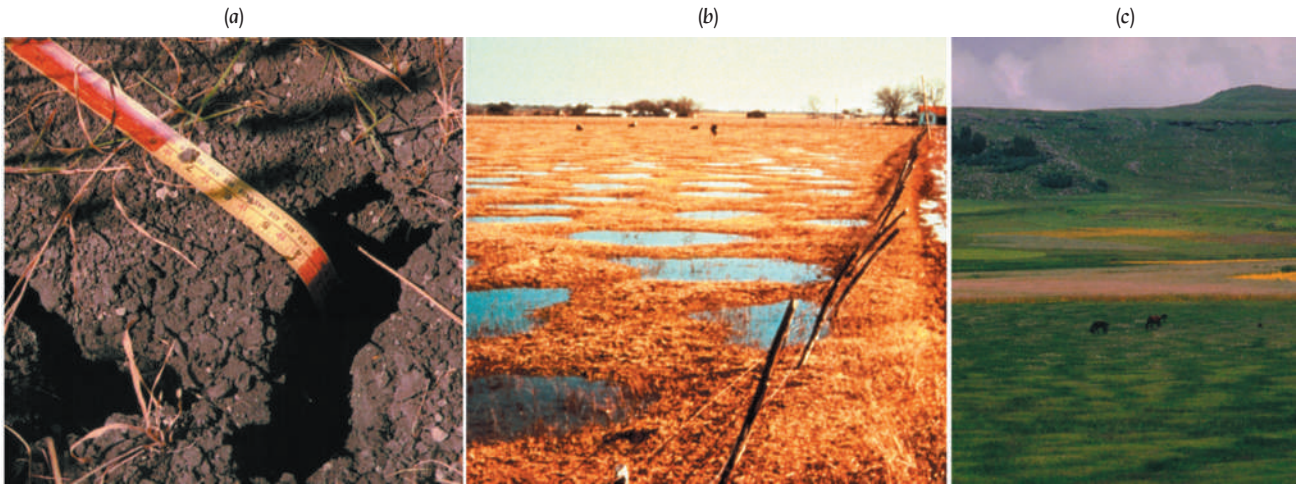

Figure 3.30 (a) *Wide cracks formed during the dry season in the surface layers of a Vertisol in Ethiopia. Surface debris can slough off into these cracks and move to subsoil. When the rains come, water can move quickly to the lower horizons, but the cracks are soon sealed, making the soils relatively impervious to the water.* (b) *Once the cracks have sealed, water may collect in the "microlows," making the gilgai relief easily visible as in the Texas Vertisol shown here.* (c) *Patterns of different grass species reflect the gilgai features of a Vertisol in the lower part of this central Ethiopia landscape* [Photos (*a*) and (*c*) courtesy of Ray R. Weil; (*b*) courtesy of K. N. Potter, USDA/ARS, Temple, Texas]

Vertisols typically develop from limestone, basalt, or other calcium- and magnesium-rich parent materials. In east Africa, they typically form in landscape depressions that collect the calcium and magnesium leached out of the surrounding upland soils. The presence of these cations encourages the formation of swelling-type clays (see Section 8.3).

Vertisols occur mostly in warm subhumid to semiarid environments, but a few (Cryerts) occur where the average soil temperatures are as low as 0 °C (see Figure 3.9). The native vegetation is usually grassland. Vertisols generally occur where the climate features alternating wet and dry periods of several months each. In dry seasons the clay shrinks, causing the soils to develop deep, wide cracks that are diagnostic for this order (Figure 3.30*a*). The surface soil generally forms granules, of which a significant number may slough off into the cracks, giving rise to a partial inversion of the soil (Figure 3.31*a*). This accounts for the association with the term *invert*, from which this order derives its name.

When the rains come, water entering the large cracks moistens the clay in the subsoils, causing it to swell. The repeated shrinking and swelling of the subsoil clay results in a kind of imperceptively slow "rocking" movement of great masses of soil. As the subsoil swells, blocks of soil shear off from the mass and rub past each other under pressure, giving rise in the subsoil to shiny, grooved, tilted surfaces called **slickensides** (Figure 3.31*c*). Eventually, this back-and-forth motion may form bowl-shaped depressions with relatively deep profiles surrounded by slightly raised areas in which little soil development has occurred and in which the parent material remains close to the surface (see Figure 3.31*b*). The resulting pattern of micro-highs and micro-lows on the land surface, called **gilgai**, is usually discernable only where the soil is untilled (Figure 3.30 *a,b*).

Distribution and Use

Globally, Vertisols comprise about 2.5% of the total land area. Large areas of Vertisols are found in India, Ethiopia, the Sudan, and northern and eastern Australia (see front papers). Smaller areas occur in sub-Saharan Africa, Mexico, Venezuela, Bolivia, and Paraguay, and east central and southern Texas and California in the US. These latter soils probably are of the Usterts or Xererts suborders, since dry conditions persist long enough for the wide cracks to stay open for periods of three months or longer.

There are several small but significant areas in the United States of Vertisols classified in the Uderts suborder because relatively moist conditions prevent cracks from persisting for more than three months of the year. These areas are located in eastern Mississippi and western Alabama (the so-called *black belt*) and along the southeast coast of Texas. An area of Cryerts is located in the Dakotas and Saskatchewan.

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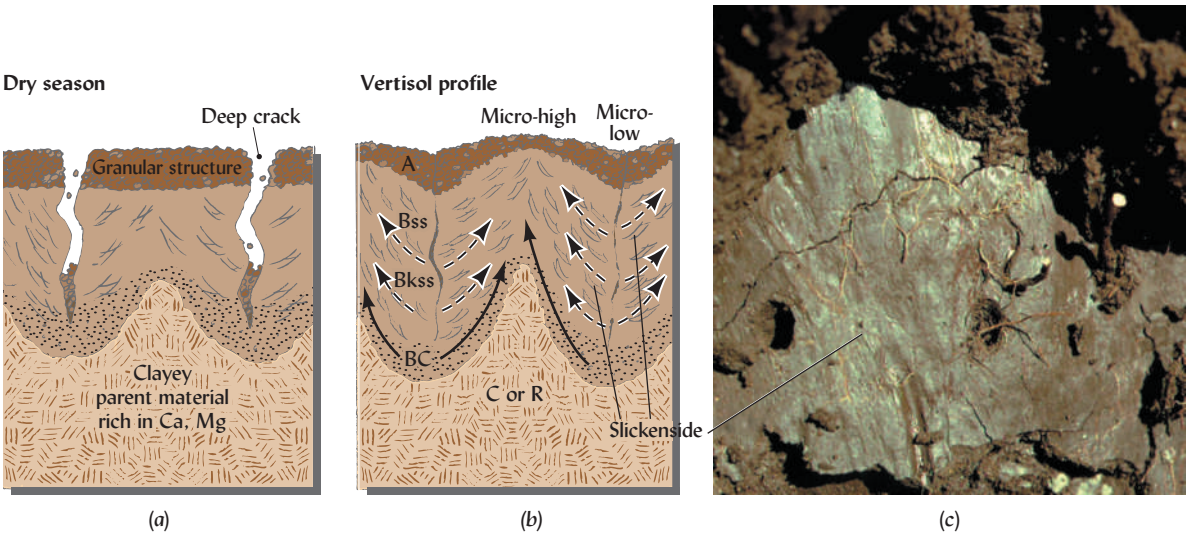

Figure 3.31 *Vertisols are high in swelling-type clay and have developed wedge-like structures in the subsoil horizons.* (a) *During the dry season, large cracks appear as the clay shrinks upon drying. Some of the surface soil granules fall into cracks under the influence of wind and animals. This action causes a partial mixing, or* inversion, *of the horizons.* (b) *During the wet season, rainwater pours down the cracks, wetting the soil near the bottom of the cracks first and then the entire profile. As the clay absorbs water, it swells the cracks shut, entrapping the collected granular soil. The increased soil volume causes lateral and upward movement of the soil mass. The soil is pushed up between the cracked areas. As the subsoil mass shears from the strain, smooth surfaces or* slickensides *form at oblique angles. These processes result in a Vertisol profile that typically exhibits* gilgai, *cracks more than 1 m deep and slickensides in a Bss horizon.* (c) *An example of a slickenside in a Vertisol. Note the grooved, shiny surface. The white spots in the lower right of the photo are calcium carbonate concretions that often accumulate in a Bkss horizon.* (Diagrams and photo courtesy of Ray R. Weil)

The high shrink–swell potential of Vertisols makes them extremely problematic for any kind of roads or buildings (Figures 3.32 and 4.58). This property also makes agricultural management very difficult. Because they are very sticky and plastic when wet and become very hard when dry, the timing of tillage operations is critical. Some farmers refer to Vertisols as *24-hour soils*, because they are said to be too wet to plow one day and too dry the next.

Even when the soil moisture is near optimal, the energy requirement for tillage is high. In areas such as those in India and the Sudan, where slow-moving animals or human power

Figure 3.32 *Utility poles appear to stagger drunkenly across a Vertisols landscape. The poles are leaning every which way because they are set into Vertisols that contain over 60% clay of a type that swells up when wet but cracks deeply and shrinks as it dries. As a result, the soil shifts or rocks back and forth with the seasons. This shrink–swell action of Vertisols makes them problematic for all kinds of construction.* (Photo courtesy of Ray R. Weil)

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are commonly used to till the soil, farmers cannot perform tillage operations on time and are limited to the use of very small tillage implements that their animals can pull through the heavy soil.

Recent research shows that the large areas of Vertisols in the tropics can produce greatly increased yields of food crops with improved soil management practices. Soils in this order are, however, very susceptible to physical degradation and erosion (despite their mainly gentle slopes), and conservation practices or reversion to rangeland are important management options to consider.

3.12 MOLLISOLS (DARK, SOFT SOILS OF GRASSLANDS)

The principal process in the formation of Mollisols is the accumulation of calcium-rich organic matter, largely from the dense root systems of prairie grasses, to form the thick, soft Mollic epipedon that characterizes soils in this order (Figures 3.33). This humus-rich surface horizon is often 60–80 cm in depth. Its cation exchange capacity (Section 8.9) is more than 50% saturated with nonacid cations (Ca^{2+}, Mg^{2+}, etc.). Mollisols in humid regions generally have higher organic matter and darker, thicker mollic epipedons than their drier region counterparts (see Section 12.8).

The surface horizon generally has granular or crumb structures, largely resulting from an abundance of organic matter, fine roots and swelling-type clays. In many cases, the highly aggregated soil is not hard when dry, hence the name *Mollisol*, implying softness (Table 3.3). In addition to the mollic epipedon, Mollisols may have an argillic (clay), natric, albic, or cambic subsurface horizon but not an oxic or spodic horizon.

Most Mollisols have developed under grass vegetation (Figure 3.34). Grassland soils of the central part of the United States, lying between Aridisols on the west and the Alfisols on the east, typify the central concept of this order. However, a few soils developed under

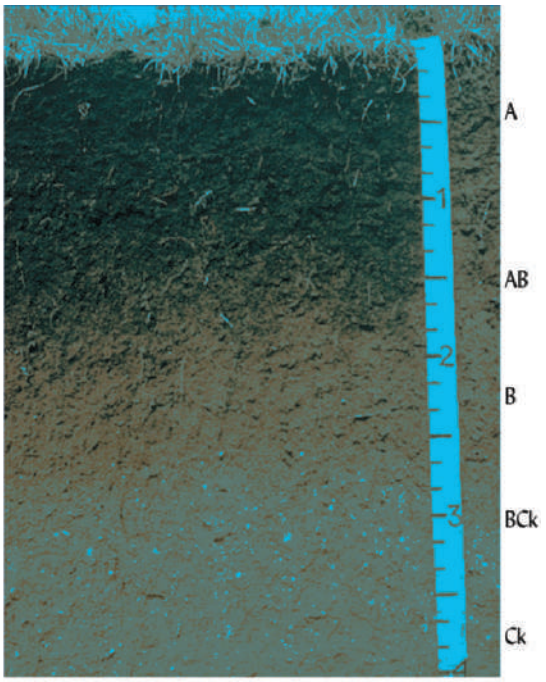

Figure 3.33 *Mollisols soil order—global distribution, land area, suborders, and a representative profile, a Typic Hapludoll from Iowa, USA. The mollic epipedon extends to 1.8 feet (scale marked in feet).* (Photo courtesy of R. W. Simonson)

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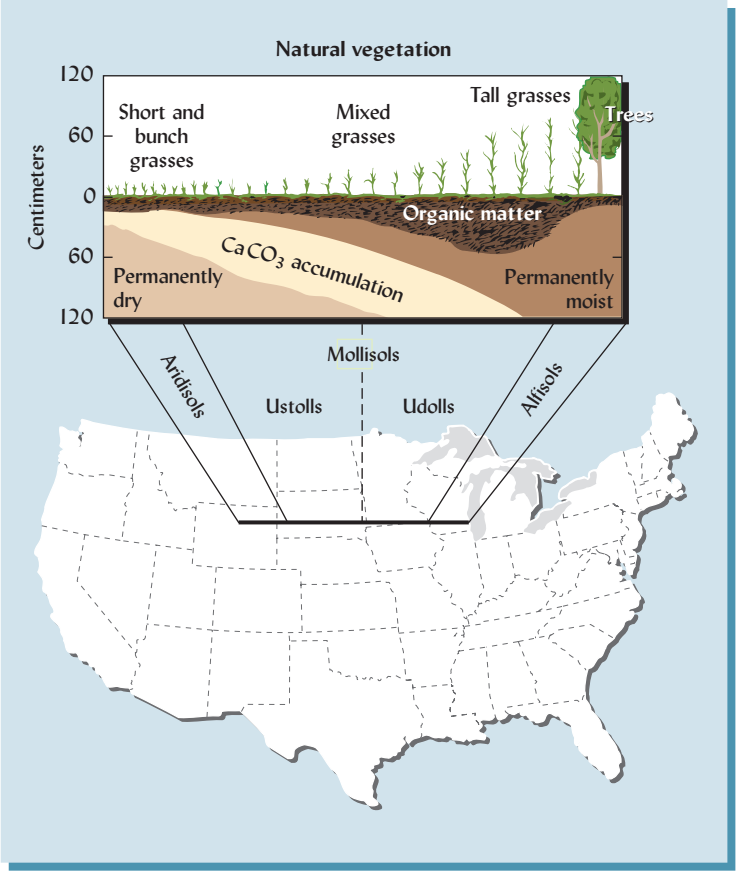

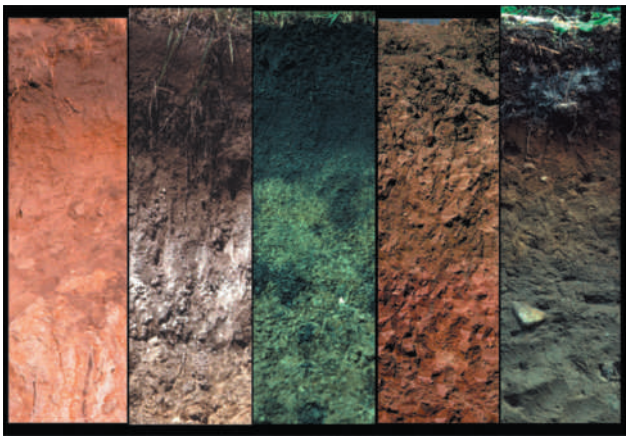

Figure 3.34 (Left) *Correlation between natural grassland vegetation and certain soil orders is graphically shown for a transect across north central United States. The controlling factor, of course, is climate. Note the deeper organic matter and deeper zone of calcium accumulation, sometimes underlain by gypsum, as one proceeds from the drier areas in the west toward the more humid region where prairie soils are found. Alfisols may develop under grassland vegetation, but more commonly occur under forests and have lighter-colored surface horizons.* (upper, left to right) *Representative profiles of Aridisols, Ustolls, Udolls, Alfisols and Spodosols.* (Profile photos courtesy of Ray R. Weil)

forest vegetation (primarily in depressions) have a mollic epipedon and are included among the Mollisols.

Distribution and Use

The largest area of Mollisols in the world stretches from east to west across the heartlands of Kazakhstan, Ukraine, and Russia. Other sizable areas are found in Mongolia, northern China, and the United States, and in northern Argentina, Paraguay, and Uruguay. Mollisols occupy only about 7% of the world's total soil area, but because of their generally high fertility, they account for a much higher percentage of total crop production.

Mollisols are extensive in North America, dominating the Great Plains and as far east as Illinois. Where soil moisture is not limiting, Udolls dominate the uplands and are associated with wet Mollisols, termed Aquolls, in the low-lying places. A region characterized by Ustolls (intermittently dry during the summer) extends from Manitoba and Saskatchewan in Canada to southern Texas. Farther west are found sizable areas of Xerolls (with a Xeric moisture regime, which is very dry in summer but moist in winter). Landscapes common for Udolls and Ustolls can be seen in Figure 3.35. Conservation of soil water is a major consideration in the management of Ustolls, in particular.

In the United States, efforts are underway to preserve the few remnants of the once vast and diverse prairie ecosystem and also to restore native grasses and wildlife habitat (see Figure 3.35, *right*). Because the high native fertility of Mollisols makes them among the world's most productive soils, few Mollisols have been left uncultivated in regions with sufficient rainfall for crop production. When they were first cleared and plowed, much of their native organic matter was oxidized, releasing nitrogen and other nutrients in sufficient quantities to produce high crop yields without the use of fertilizers. Even after more than a century of cultivation, these Mollisols are among the most productive soils, although continuous cultivation with row crops has led to serious deterioration of soil structure and to soil erosion where the land is sloping.

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Figure 3.35 *Typical landscapes dominated by Ustolls (eastern Colorado, USA,* left*) and Udolls (Iowa, USA,* right*). These types of productive soils produce much of the food and feed in the world.* (Photos courtesy of Ray R. Weil, *left*, and Tim McGabe, USDA/NRCS, *right*)

3.13 ALFISOLS (ARGILLIC OR NATRIC HORIZON, MODERATELY LEACHED)

The Alfisols are more strongly weathered than soils in the orders just discussed, but less so than Spodosols, Ultisols, and Oxisols (see following). They are found in cool to hot humid areas (see Figure 3.9) as well as in the semiarid tropics and Mediterranean climates. Most often, Alfisols develop under native deciduous forests, although in some cases, as in parts of Africa and California, USA, savanna (mixed trees and grass) is the native vegetation.

Alfisols are characterized by a subsurface diagnostic horizon in which silicate clay has accumulated by illuviation (see Figure 3.36). Clay skins or other signs of clay movement are present in such a B horizon (see Figure 3.5). In Alfisols, this clay-rich horizon is only moderately leached, and its cation exchange capacity is more than 35% saturated with nonacid cations (Ca^{2+}, Mg^{2+}, etc.). In most Alfisols this horizon is termed *argillic* because of its accumulation of silicate clays. The horizon is termed *natric* if, in addition to having an accumulation of clay, it is more than 15% saturated with sodium and has prismatic or columnar structure (see Figure 4.13). In some Alfisols in subhumid tropical regions, the accumulation is termed a *kandic* horizon (from the mineral kandite) because the clay minerals are more highly weathered and have a low cation exchange capacity.

9.6% of global ice-free land

Suborders are:
- Aqualfs (wet)
- Cryalfs (cold)
- Udalfs (humid)
- Ustalfs (moist/dry)
- Xeralfs (dry summers, moist winters)

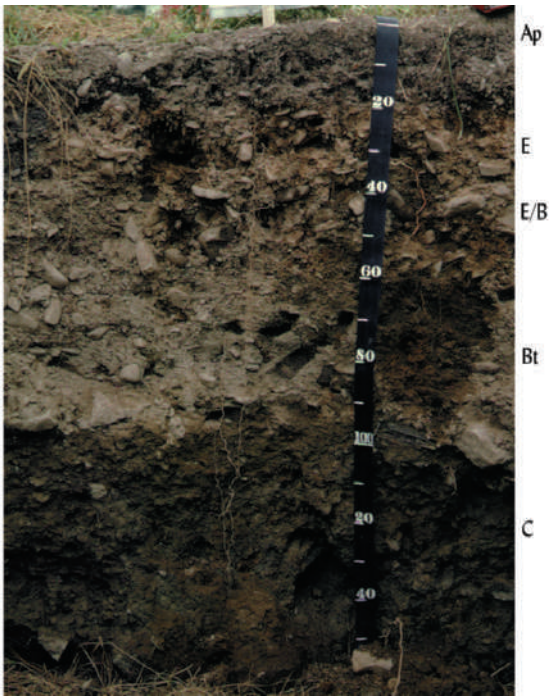

Figure 3.36 *Alfisols soil order—global distribution, land area, suborders, and a representative profile, a Glossic Hapludalf from New York, USA. Scale in centimeters.* (Photo courtesy of Ray R. Weil)

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Figure 3.37 *A landscape in southern Portugal dominated by Xeralfs. Most of the original forest has been cleared and the soils plowed for production of winter cereals and grapes.* (Photo courtesy of Ray R. Weil)

Alfisols very rarely have a mollic epipedon, for such soils would be classified in the Argiudolls or other suborder of Mollisols with an argillic horizon. Instead, Alfisols typically have a relatively thin, gray to brown ochric epipedon (Figure 3.36 shows an example) or an umbric epipedon. Those formed under deciduous temperate forests commonly have a light-colored, leached *albic* E horizon immediately under the A horizon (see Figures 1.15 and 3.33).

Distribution and Use

Udalfs (humid region Alfisols) dominate large areas in central China, England, France, central Europe, southeastern Australia, and north central United States. There are sizable areas of Xeralfs (Alfisols in regions of dry summers and moist winters) in southwestern Australia, Italy, central Spain and Portugal, and central California, USA (Figure 3.37). Cryalfs (very cold) can be found in northern Europe, extending from the Baltic States through western Russia; in Siberia; in the Rocky Mountains; in south-central Canada; and in Minnesota, USA. Where summers are hot and dry, including areas in sub-Saharan Africa, eastern Brazil, eastern India, southeastern Asia, and Texas and New Mexico in the US, Ustalfs are prominent. Many Alfisols landscapes include wet depressions characterized by Aqualfs.

In general, Alfisols are productive soils. Good hardwood forest growth and crop yields are favored by their medium to high nonacid cation saturation status, generally favorable texture, and location (except for some Xeralfs) in regions with enough rainfall to support good plant growth for at least part of the year. In the United States these soils rank favorably with the Mollisols and Ultisols in their productive capacity. Many Alfisols, especially the sandier ones, are quite susceptible to erosion by heavy rains if deprived of their natural surface litter. Alfisols in Udic moisture regimes are sufficiently acidic in the A horizon to require amendment with limestone for many kinds of plants (see Chapter 9).

3.14 ULTISOLS (ARGILLIC HORIZON, HIGHLY LEACHED)

The principal processes involved in forming Ultisols are clay mineral weathering, translocation of clays to accumulate in an argillic or kandic horizon, and leaching of nonacid cations from the profile. Most Ultisols have developed under moist conditions in warm to tropical climates. Ultisols are formed on old land surfaces, usually under forest vegetation, although savanna or even swamp vegetation is also common. They often have an ochric or umbric epipedon but are characterized by a relatively acidic B horizon that has less than 35% of the exchange capacity satisfied with nonacid cations. The clay accumulation may be either an argillic horizon or, if the clay is of low activity, a kandic horizon. Ultisols commonly have both an epipedon and a subsoil that is quite acid and low in plant nutrients.

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8.5% of global ice-free land

Suborders are:
- Aquults (wet)
- Humults (high humus)
- Udults (humid)
- Ustults (moist/dry)
- Xerults (dry summers, moist winters)

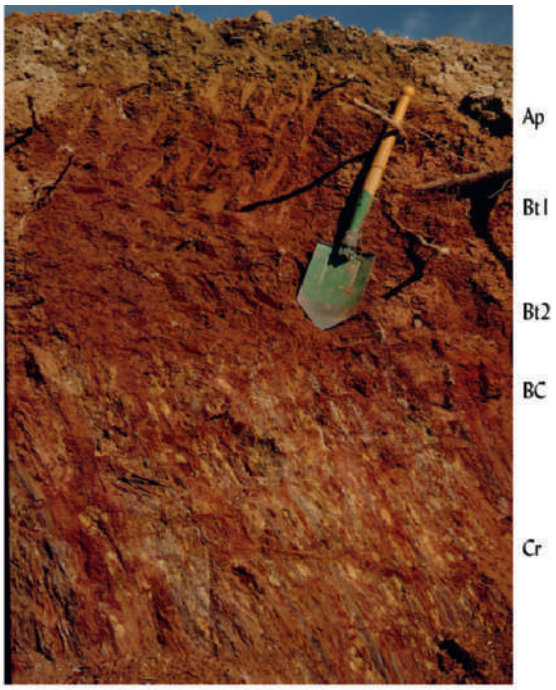

Figure 3.38 *Ultisols soil order—global distribution, land area, suborders, and a representative profile, a Typic hapludult from central Virginia, USA, showing rock structure in the saprolite below the 60-cm-long shovel.* (Photo courtesy of Ray R. Weil)

Ultisols are more highly weathered and acidic than Alfisols but less acid than Spodosols and less highly weathered than the Oxisols. Except for the wetter members of the order, their subsurface horizons are commonly red or yellow in color, evidence of accumulations of oxides of iron (see Figure 3.38). Certain Ultisols (as well as certain Alfisols in tropical regions) that formed under fluctuating wetness conditions exhibit horizons of iron-rich mottled material called ***plinthite*** (see Figure 3.39). This material is soft and can be easily dug from the profile so long as it remains moist. When dried in the air, however, plinthite hardens irreversibly into a kind of ironstone that is virtually useless for cultivation (Figure 3.39, *right*) but can be used to make durable bricks for building (Figure 3.39, *left*).

Distribution and Use

Large areas of Udults are also located in southeastern Asia, in southern China, and southeastern United States. Extensive areas of Ultisols are found in the humid tropics in close association with some Oxisols. Important agricultural areas are found in southern Brazil and Paraguay.

Humults (high in organic matter) are found in the United States in Hawaii and in western California, Oregon, and Washington. Humults are also present in the highlands of some

Figure 3.39 *Plinthite is a feature of some Ultisols* (middle) *that formed under fluctuating water table conditions such that iron alternately dissolved and precipitated creating red iron-rich and whitish iron-depleted splotches of soil color. The material is soft when in place and moist, but hardens irreversibly when dried in the air. Blocks of the material* (*also termed laterite*) *can be cut and dried into durable bricks* (left). *Plinthite can be a serious limitation for plant growth if the hardened form of the material occurs at a shallow depth. It often occurs as hard cemented layers, a chunk of which is seen on the soil surface in an African field* (right). (Photos courtesy of Ray R. Weil)

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Figure 3.40 *The soils in this high-elevation, tropical area of South Asia are Ultisols in the suborder Humults. These soils are being intensively used both for house construction and for market gardens. The combination of a favorable climate and soils that are high in organic matter (Humults have at least 9% down to the upper part of the B horizon) and respond well to fertilizer has encouraged local residents to use every bit of the land in producing vegetables to supplement their incomes.* (Photo courtesy of Ray R. Weil)

tropical countries. Xerults (Ultisols in Mediterranean-type climates) occur locally in southern Oregon and northern and eastern California in the US. Ustults are found in semiarid areas with a marked dry season. Together with the Ustalfs, the Ustults occupy large areas in Africa and India (Figure 3.40). Ultisols are prominent on the east and northeast coasts of Australia (see front papers).

Although Ultisols are not naturally as fertile as Alfisols or Mollisols, they respond well to good management. They are located mostly in regions of long growing seasons and of ample moisture for good crop production (Figure 3.40). The silicate clays of Ultisols are usually of the nonsticky type, which, along with the presence of iron oxides and aluminum, assures ready workability. With adequate management of fertilizers, lime, and organic matter, Ultisols can be quite productive for agriculture. In the United States, well-managed Ultisols compete well with Alfisols and also support highly productive commercial softwood and hardwood forests.

3.15 SPODOSOLS (ACID, SANDY, FOREST SOILS, HIGHLY LEACHED)

Intensive acid leaching of coarse-textured, acid parent materials is the principal process leading to the formation of Spodosols (Figure 3.41). These are mineral soils with a *spodic* horizon, a subsurface accumulation of illuviated organic matter, and an accumulation of aluminum oxides with or without iron oxides. This usually thin, dark, illuvial horizon typically underlies a light, ash-colored, eluvial *albic* horizon. The combination of bright white E and very dark A and B horizons is visually quite striking and makes for some of the most easily recognized and some would say most beautiful of soil profiles (see Figure 3.42).

Spodosols form under forest vegetation, especially under coniferous species whose needles are low in base-forming cations like calcium and high in acid resins. As this acid litter decomposes, strongly acid organic compounds are released and carried down into the permeable profile by percolating waters. Some of the leaching organic compounds may precipitate and form a black-colored Bh horizon. Leaching organic acids bind with iron and aluminum, removing these metals from the A and E horizons and carrying them downward. This iron and aluminum eventually precipitates in a reddish-brown-colored Bs horizon, usually just below the black-colored Bh horizon. Together, the Bh and Bs horizons constitute the spodic diagnostic horizon that defines the Spodosols. The depth at which the spodic horizon forms can vary from less than 20 cm to several meters. As iron oxides (and most other minerals except quartz) are stripped from the E horizon by the organic leaching process, this horizon may become a nearly white albic diagnostic horizon that consists mainly of clean quartz sand. The leaching and precipitation often occur along wavy wetting fronts, thus yielding the striking profiles seen in Spodosols (Figure 3.42, *left*).

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2.6% of global ice-free land

Suborders are:
Aquods (wet)
Cryods (cold)
Gelods (very cold)
Humods (humus)
Orthods (typical)

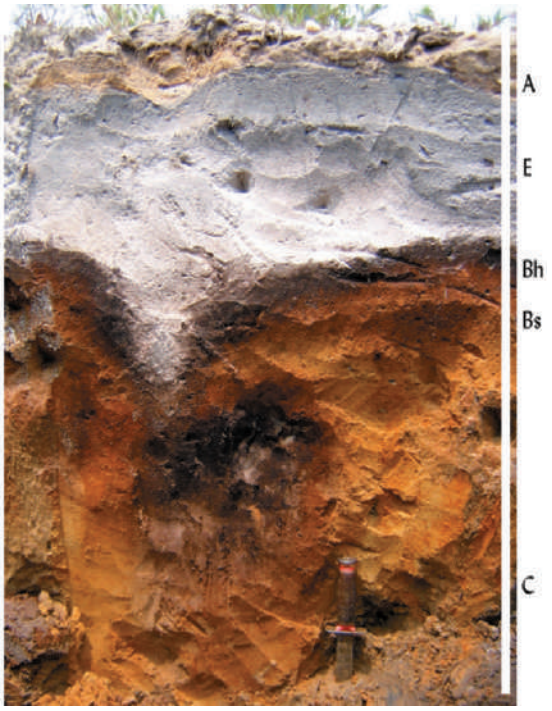

Figure 3.41 *Spodosols soil order—global distribution, land area, suborders, and a representative profile, a Typic Haplorthod from New Jersey, USA, showing pronounced albic and spodic horizons. Scale marked in 10 cm.* (Photo courtesy of Ray R. Weil)

Distribution and Use

Spodosols generally occur in regions with cool, moist climates (see Figure 3.9), but some also can be found in moist tropical and subtropical areas.

Large areas of Spodosols are found in northern Europe and Russia, in central and eastern Canada, and in northern United States. Small but ecologically important areas occur in the southern part of South America and in the cool mountainous areas of temperate regions.

Most Spodosols are Orthods, soils that typify the central concept of Spodosols described previously. Some, however, are Aquods because they are seasonally saturated with water and possess characteristics associated with wetness. Important areas of Aquods occur in Florida, USA, and other areas with warm climates.

Spodosols are naturally quite acid and infertile. When properly fertilized, however, they can become quite productive. For example, most potato-producing soils of northern Europe and Maine, USA, are Spodosols, as are some of the vegetable- and fruit-producing soils of Florida, Michigan, and Wisconsin in the US. Because of their sandy nature and occurrence in regions of high rainfall, groundwater contamination by leaching of soluble fertilizers and pesticides has proved to be a serious problem where these soils are used in crop production. Many once cultivated Spodosols have been abandoned and are now covered mostly with forests, the vegetation under which they originally developed. Most Spodosols should remain as forest habitats. Because they are already quite acid and poorly buffered, many Spodosols and the lakes in watersheds dominated by soils of this order are susceptible to damage from acid rain (see Section 9.6).

3.16 OXISOLS (OXIC HORIZON, HIGHLY WEATHERED)

The Oxisols are the most highly weathered soils in the classification system (see Figure 3.8). They form in hot climates with nearly year-round moist conditions; hence, the native vegetation is generally tropical rain forest. However, some Oxisols (Ustox) are found in areas that are today much drier than was the case when the soils were forming their oxic characteristics.

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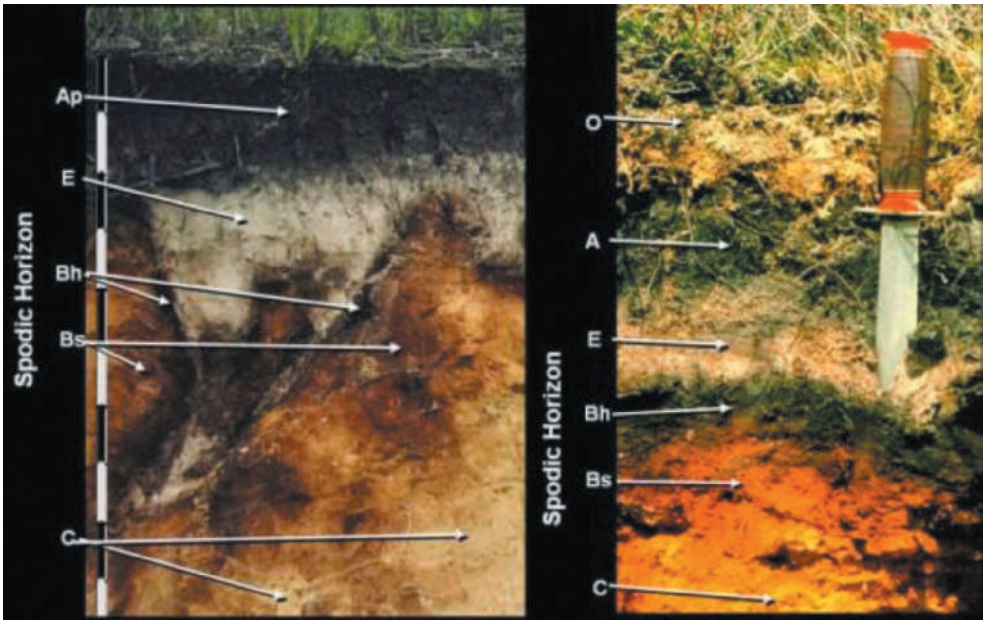

Figure 3.42 (Left) *A Spodosol in northern Michigan, USA, exhibits discontinuous, wavy Bh and Bs genetic horizons, which comprise the relatively deep spodic diagnostic horizon. The nearly white, discontinuous eluvial horizon (E) consists mainly of uncoated quartz sand particles and is an albic diagnostic horizon. The dark, organic-enriched surface horizon (an ochric diagnostic horizon) shows the smooth lower boundary and uniform thickness characteristic of an Ap horizon formed by plowing after the original coniferous forest was cleared.* (Right) *A much shallower Spodosol in Scotland also exhibits a spodic diagnostic horizon comprised of Bh and Bs genetic horizons. Above the spodic horizon is the light-colored albic horizon (E) and above that, the darker ochric (A) horizon. These horizons, in combination with the relatively thick surface layer of pine needles in various states of decay (the O horizon), suggest an undisturbed forest floor. Both soils formed from the sandy parent material evident in their C horizons. Spodosols are typically sandy, acid, infertile, and best suited to supporting the coniferous forest vegetation under which they usually form. Scale at left marked every 10 cm, knife at right has a 12-cm-long handle.* (Photos courtesy of Ray R. Weil)

Their most important diagnostic feature is a deep oxic subsurface horizon (Figure 3.43). This horizon is generally very high in clay-size particles dominated by hydrous oxides of iron and aluminum. Weathering and intense leaching have removed much of the silica from the silicate materials in this horizon. Some quartz and 1:1-type silicate clay minerals remain, but the hydrous oxides are dominant (see Chapter 8 for information on the various clay minerals). The epipedon in most Oxisols is either ochric or umbric. Usually the boundaries between subsurface horizons are indistinct, giving the subsoil a relatively uniform appearance with depth.

The clay content of Oxisols is generally high, but the clays are of the low-activity, nonsticky type. Consequently, when the clay dries out, it is not hard and cloddy but is easily worked. Also, Oxisols are resistant to compaction, so water moves freely through the profile. The depth of weathering in Oxisols is typically much greater than for most of the other soils, 20 m or more having been observed. The low-activity clays have a very limited capacity to hold nutrient cations such as Ca^{2+}, Mg^{2+}, and K^{+}, so they are typically of low natural fertility and moderately acid. The high concentration of iron and aluminum oxides also gives these soils a capacity to bind so tightly with what little P is present that P deficiency often limits plant growth once the natural vegetation is disturbed.

Road and building construction is relatively easily accomplished on most Oxisols because these soils are easily excavated, do not shrink and swell, and are physically very stable on slopes (Figure 3.44). The very stable aggregation of the clays, stimulated largely by iron compounds, makes these soils quite resistant to erosion.

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7.6% of global ice-free land

Suborders are:
- Aquox (wet)
- Perox (very humid)
- Torrox (hot, dry)
- Udox (humid)
- Ustox (moist/dry)

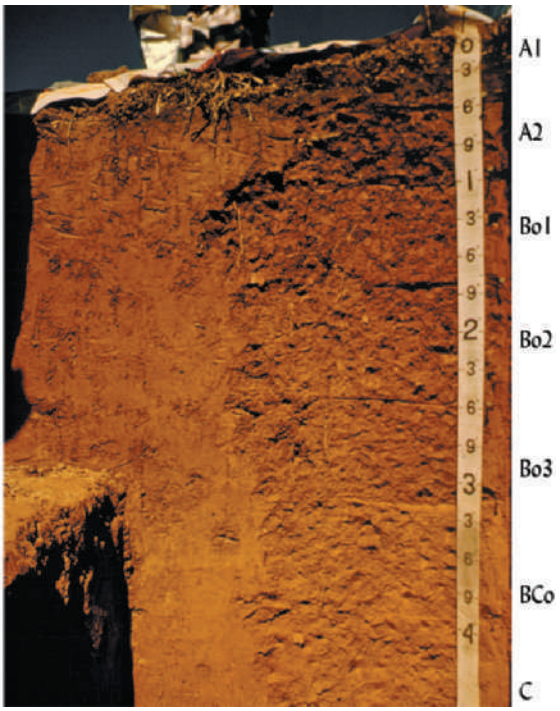

Figure 3.43 *Oxisols soil order—global distribution, land area, suborders, and a representative profile, a Eudeptic Haplorthox from Puerto Rico, USA. Scale marked in feet and inches.* (Photo courtesy of Soil Science Society of America)

Distribution and Use

Oxisols occupy old land surfaces that have not been disturbed by glaciation or erosion. Although nearly all Oxisols occur in the tropics, most tropical soils are *not* Oxisols. Large areas of Oxisols occur in South America and Africa (see front papers). Some of the areas of the Amazon basin previously mapped as Oxisols are in reality dominated by Ultisols and other soils. Udox (Oxisols having little or no dry season) occur in northern Brazil and neighboring countries as well as in the Caribbean area (Figure 3.44). Important areas of Ustox (hot, dry summers) occur in Brazil to the south of the Udox. In the humid areas of central Africa, Oxisols are prominent and in some cases dominant.

Relatively less is known about Oxisols than about most other soil orders. They occur in large geographic areas, often associated with Ultisols. Millions of people in the tropics depend on them for food and fiber production. However, because of their low natural fertility, most Oxisols have been left under forest vegetation or are farmed by shifting cultivation methods.

Figure 3.44 *An Oxisols landscape and profile in a rain-forest area of Puerto Rico illustrating the dusky, red colors, rather homogenous profile and physical stability characteristic of many Oxisols.* (Photos courtesy of Ray R. Weil)

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Nutrient cycling by deep-rooted trees is especially important to the productivity of these soils. Probably the best use of Oxisols, other than supporting rain forests, is the culture of mixed-canopy perennial crops, especially tree crops. Such cultures can restore the nutrient cycling system that characterized the soil–plant relationships before the rain forest was removed.

3.17 LOWER-LEVEL CATEGORIES IN *SOIL TAXONOMY*

Suborders

As indicated next to the global distribution maps in previous sections, soils within each order are grouped into suborders on the basis of soil properties that reflect major environmental controls on current soil-forming processes. Many suborders are indicative of the moisture regime or, less frequently, the temperature regime under which the soils are found. Thus, soils formed under wet conditions generally are identified under separate suborders (e.g., Aquents, Aquerts, and Aquepts), as being wet soils.

To determine the relationship between suborder names and soil characteristics, refer to Table 3.4. Here the formative elements for suborder names are identified and their

Table 3.4
FORMATIVE ELEMENTS IN NAMES OF SUBORDERS IN *SOIL TAXONOMY*

Formative Element	Derivation	Connotation of Formative Element
alb	L. *albus*, white	Presence of albic horizon (a bleached eluvial horizon)
aqu	L. *aqua*, water	Characteristics associated with wetness
ar	L. *arare*, to plow	Mixed horizons
arg	L. *argilla*, white clay	Presence of argillic horizon (a horizon with illuvial clay)
calc	L. *calcis*, lime	Presence of calcic horizon
camb	L. *cambriare*, to change	Presence of cambic horizon
cry	Gk. *kryos*, icy cold	Cold
dur	L. *durus*, hard	Presence of a duripan
fibr	L. *fibra*, fiber	Least-decomposed stage
fluv	L. *fluvius*, river	Floodplains
fol	L. *folia*, leaf	Mass of leaves
gel	Gk. *gelid*, cold	Cold
gyps	L. *gypsum*, gypsum	Presence of gypsic horizon
hem	Gk. *hemi*, half	Intermediate stage of decomposition
hist	Gk. *histos*, tissue	Presence of histic epipedon
hum	L. *humus*, earth	Presence of organic matter
orth	Gk. *orthos*, true	The common ones
per	L. *per*, throughout time	Of year-round humid climates, perudic moisture regime
psamm	Gk. *psammos*, sand	Sand textures
rend	Modified from Rendzina	Rendzina-like—high in carbonates
sal	L. *sal*, salt	Presence of salic (saline) horizon
sapr	Gk. *sapros*, rotten	Most decomposed stage
torr	L. *torridus*, hot and dry	Usually dry
turb	L. *turbidus*, disturbed	Cryoturbation
ud	L. *udus*, humid	Of humid climates
ust	L. *ustus*, burnt	Of dry climates, usually hot in summer
vitr	L. *vitreus*, glass	Resembling glass
wass	G. *wasser*, water	Positive water potential at the soil surface year round
xer	Gk. *xeros*, dry	Dry summers, moist winters

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connotations given. Thus, the Ustolls are dry Mollisols. Likewise, soils in the Udults suborder (from the Latin *udus*, humid) are moist Ultisols.

Great Groups

The great groups are subdivisions of suborders. More than 400 great groups are recognized. They are defined largely by the presence or absence of diagnostic horizons and the arrangements of those horizons. These horizon designations are included in the list of formative elements for the names of great groups shown in Table 3.5. Note that these formative elements refer to epipedons such as umbric and ochric (see Table 3.1 and Figure 3.3), to subsurface horizons such as argillic and natric, and to certain diagnostic impervious layers such as duripans and fragipans (see Figure 3.30).

Remember that the great group names are made up of these formative elements attached as prefixes to the names of suborders in which the great groups occur. Thus, Ustolls with a natric horizon (high in sodium) belong to the Natrustolls great group. As can be seen in the example discussed in *Box 3.2*, soil descriptions at the great group level can provide important information not indicated at the higher, more general levels of classification.

Table 3.5
FORMATIVE ELEMENTS FOR NAMES OF GREAT GROUPS AND THEIR CONNOTATION
These formative elements combined with the appropriate suborder names give the great group names.

Formative Element	Connotation	Formative Element	Connotation
acr	Extreme weathering	hist	Presence of organic materials
al	High aluminum, low iron	hum	Humus
alb	Albic horizon	hydr	Water
and	Ando-like	kand	Low-activity 1:1 silicate clay
anhy	Anhydrous	kanhapl	Kandic and minimum horizon
aqu	Water saturated	luv, lu	Illuvial
argi	Argillic horizon	melan	Melanic epipedon
calc, calci	Calcic horizon	molli	With a mollic epipedon
camb	Cambic horizon	natr	Presence of a natric horizon
cry	Cold	pale	Old development
dur	Duripan	petr	Cemented horizon
dystr, dys	Low base saturation	plac	Thin pan
endo	Fully water saturated	plagg	Plaggen horizon
epi	Perched water table	plinth	Plinthite
eutr	High base saturation	psamm	Sand texture
ferr	Iron	quartz	High quartz
fibr	Least decomposed	rhod	Dark red colors
fluv	Floodplain	sal	Salic horizon
fol	Mass of leaves	sapr	Most decomposed
fragi	Fragipan	somb	Dark horizon
fragloss	Combination of *fragi* and *gloss*	sphagn	Sphagnum moss
frassi	Inundated but low in salts	sulf	Sulfuric
fulv	Light-colored melanic horizon	torr	Usually dry and hot
gel	Gelic temperature regine	ud	Humid climates
glaci	Glacic layer	umbr	Umbric epipedon
gyps	Gypsic horizon	ust	Dry climate, usually hot in summer
gloss	Tongued	verm	Wormy or mixed by animals
hal	Salty	vitr	Glass
hapl	Minimum horizon	xanthic	Red/yellow colors from iron
hem	Intermediate decomposition	xer	Dry summers, moist winters

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BOX 3.2

GREAT GROUPS, FRAGIPANS, AND ARCHAEOLOGIC DIGS

Soil Taxonomy is a communications tool that helps scientists and land managers share information. In this box we will see how misclassification, even at a lower level in *Soil Taxonomy*, such as the great group, can have costly ramifications.

In order to preserve our historical and prehistorical heritage, laws require that an archaeological impact statement be prepared prior to starting major construction work on the land. The archaeological impact is usually assessed in three phases. Selected sites are then studied by archaeologists, with the hope that at least some of the artifacts can be preserved and interpreted before construction activities obliterate them forever. Only a few relatively small sites can be subjected to actual archaeological digs because of the expensive skilled hand labor involved (Figure 3.45).

Such an archaeological impact study was ordered as a precursor to construction of a new highway in a mid-Atlantic state. In the first phase, a consulting company gathered soils and other information from maps, aerial photographs, and field investigations to determine where neolithic people may have occupied sites. Then the consultants identified about 12 ha of land where artifacts indicated significant neolithic activities. The soils in one area were mapped mainly as Typic Dystrudepts. These soils formed in old colluvial and alluvial materials that, many thousands of years ago, had been along a river bank. Several representative soil profiles were examined by digging pits with a backhoe. The different horizons were described, and it was determined in which horizons artifacts were most likely to be found. What was not noted was the presence in these soils of a fragipan, a dense, brittle layer that is extremely difficult to excavate using hand tools.

A fragipan is a subsurface diagnostic horizon used to classify soils, usually at the great group or subgroup level (see Figure 3.46). Its presence would distinguish Fragiudepts from Dystrudepts.

When it came time for the actual hand excavation of sites to recover artifacts, a second consulting company was awarded the contract. Unfortunately, their bid on the contract was based on soil descriptions that did not specifically classify the soils as Fragiudepts—soils with very dense, brittle, hard fragipans in the layer that would need to be excavated by hand. So difficult was this layer to excavate and sift through by hand that it nearly doubled the cost of the excavation—an additional expense of about $1 million. Needless to say, there ensued a controversy as to whether this cost would be borne by the consulting firm that bid with faulty soils data, the original consulting firm that failed to adequately describe the presence of the fragipan, or the highway construction company that was paying for the survey.

Figure 3.45 *An archaeological dig.* (Photo courtesy of Antonio Segovia, University of Maryland)

(continued)

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BOX 3.2

GREAT GROUPS, FRAGIPANS, AND ARCHAEOLOGIC DIGS *(CONTINUED)*

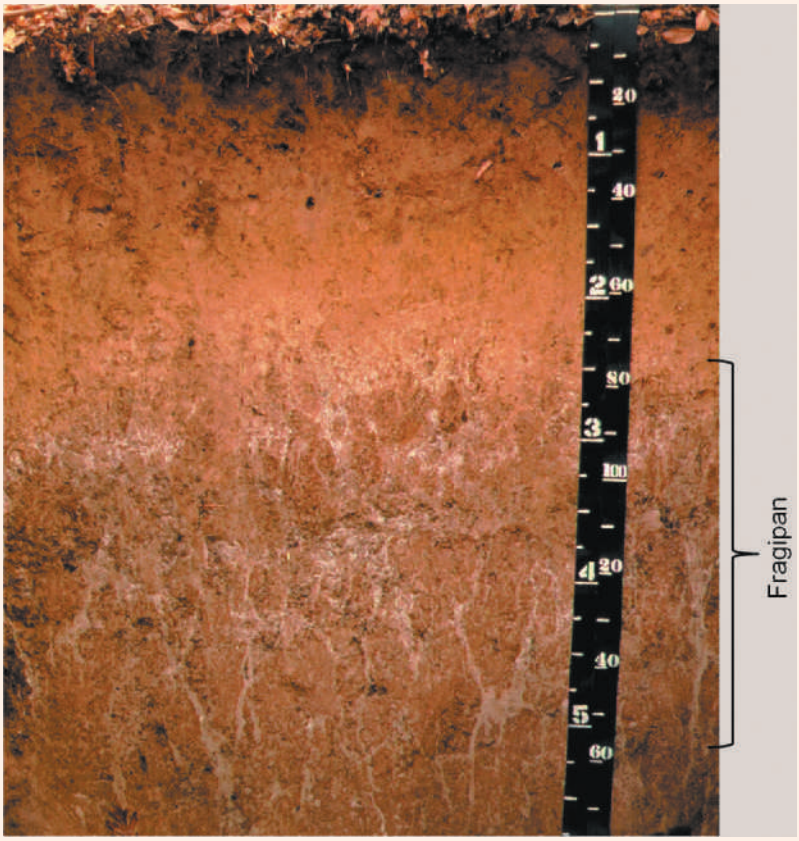

Figure 3.46 *A forested fragiudalf in Missouri, USA, containing a typical well-developed, fragile fragipan with coarse prismatic structure (outlined by gray, iron-depleted coatings). Fragipans (usually Bx or Cx horizons) are extremely dense and brittle. They consist mainly of silt, often with considerable sand, but not very much clay. One sign of encountering a fragipan in the field is the ringing noise that your shovel will make when you attempt to excavate it. Digging through a fragipan is almost like digging concrete. Plant roots cannot penetrate this layer. Yet, once a piece of a fragipan is broken loose, it fairly easily crushes with hand pressure. It does not squash or act in a plastic manner as a claypan would; instead, it bursts in a brittle manner.* (Photo courtesy of Fred Rhoton, Agricultural Research Service, U.S. Department of Agriculture)

This episode gives us an example of the practical importance of soil classification. The formative element *Fragi* in a soil great group name warns of the presence of a dense, impermeable layer that will be very difficult to excavate, will restrict root growth (often causing trees to topple in the wind or become severely stunted), may cause a perched water table (epiaquic conditions), and will interfere with proper percolation in a septic drain field.

The names of selected great groups from two orders are given in Table 3.6. This list illustrates again the usefulness of *Soil Taxonomy*, especially the nomenclature it employs. The names identify the suborder and order in which the great groups are found. Thus, Argiudolls are Mollisols of the Udolls suborder characterized by an argillic horizon. Cross-reference to Table 3.5 identifies the specific characteristics separating the great group classes from each other.

Note from Table 3.6 that not all possible combinations of great group prefixes and suborders are used. In some cases a particular combination does not exist. For example, Aquolls occur in lowland areas but not on very old landscapes. Hence, there are no "Paleaquolls." Also, since *all* Ultisols contain an argillic horizon, the use of terms such as *Argiudults* would be redundant.

Subgroups

Subgroups are subdivisions of the great groups. More than 2600 subgroups are recognized. The central concept of a great group makes up one subgroup, termed *Typic*. Thus, the Typic

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Table 3.6
EXAMPLES OF GREAT GROUP NAMES FOR SELECTED SUBORDERS IN THE MOLLISOL AND ULTISOL ORDERS

	Dominant Feature of Great Group			
	Argillic Horizon	Central Concept with No Distinguishing Features	Old Land Surfaces	Fragipan
Mollisols				
1. Aquolls (wet)	Argi*aquolls*	Hapl*aquolls*	—	—
2. Udolls (moist)	Argi*udolls*	Hapl*udolls*	Pale*udolls*	—
3. Ustolls (dry)	Argi*ustolls*	Hapl*ustolls*	Pale*ustolls*	—
4. Xerolls (Med.)[a]	Argi*xerolls*	Haplo*xerolls*	Pale*xerolls*	—
Ultisols				
1. Aquults (wet)	—	—	Pale*aquults*	Fragi*aquults*
2. Udults (moist)	—	Hapl*udults*	Pale*udults*	Fragi*udults*
3. Ustults (dry)	—	Hapl*ustults*	Pale*ustults*	—
4. Xerults (Med.)[a]	—	Haplo*xerults*	Pale*xerults*	—

[a]Med. = Mediterranean climate; distinct dry period in summer.

Hapludolls subgroup typifies the Hapludolls great group. Other subgroups may have characteristics that *intergrade* between those of the central concept and soils of other orders, suborders, or great groups. A Hapludoll with restricted drainage (but not wet enough to be an Aquoll) would be classified as an Aquic Hapludoll. Some intergrades may have properties in common with other orders or with other great groups. Thus, soils in the Entic Hapludolls subgroup are very weakly developed Mollisols, close to being in the Entisols order.

Other subgroups are considered to be extragrades rather than intergrades. That is, they exhibit special characterisitics that do not suggest they are close to being in another soil group. For example, a Hapudoll with evidence of intense earthworm activity would fall in the Vermic Hapludolls subgroup.

Subgroups for Human-Influenced Soils Human-influenced (anthropic) soil characteristics are now recognized as subgroup extragrades in Soil Taxonomy. Subgroup adjectives for human influenced characteristics include Plaggic (having a Plaggen epipedon), Anthropic (having an Anthropic epipedon), Anthraquic (e.g., rice paddy soils), Anthrodensic (human compacted soils), Anthraltic (formed in human altered, typically bulldozed, material) and Anthroportic (formed in human transported material, such as dredge spoil). As an examples, see the Anthraltic Xerorthent shown in Figure 19.23 and the Anthroportic Udorthent formed in human transported dredge spoil material in Figure 2.32.

Families

Within a subgroup, soils fall into a particular family if, at a specified depth, they have similar physical and chemical properties affecting the growth of plant roots. About 8000 families have been identified. The criteria used include broad classes of particle size, mineralogy, cation exchange activity of the clay, temperature, and depth of the soil penetrable by roots. Table 3.7 gives examples of the classes used. Terms such as *loamy*, *sandy*, and *clayey* are used to identify the broad particle size classes. Terms used to describe the mineralogical classes include *smectitic*, *kaolinitic*, *siliceous*, *carbonatic*, and *mixed*. The clays are described as *superactive*, *active*,

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Table 3.7
SOME COMMONLY USED PARTICLE-SIZE, MINERALOGY, CATION EXCHANGE ACTIVITY, AND TEMPERATURE CLASSES USED TO DIFFERENTIATE SOIL FAMILIES

The characteristics generally apply to the subsoil or 50 cm depth. Other criteria used to differentiate soil families (but not shown here) include the presence of calcareous or highly aluminum toxic (allic) properties, extremely shallow depth (shallow or micro), degree of cementation, coatings on sand grains, and the presence of permanent cracks or human artifacts.

		Cation Exchange Activity Class[b]		Soil Temperature Regime Class		
Particle-Size Class	Mineralogy Class	Term	CEC /% clay	Mean Annual Temperature, °C	>6 °C Difference Between Summer and Winter	<6 °C Difference Between Summer and Winter
Ashy	Mixed	Superactive	>0.60	<−10	Hypergelic[c]	—
Fragmental	Micaceous	Active	0.4–0.6	−4 to −10	Pergelic[c]	—
Sandy-skeletal[a]	Siliceous	Semiactive	0.24–0.4	+1 to −4	Subgelic[c]	—
Sandy	Kaolinitic	Subactive	<0.24	<+8	Cryic	—
Loamy	Smectitic			<+8	Frigid[d]	Isofrigid
Clayey	Gibbsitic			+8 to +15	Mesic	Isomesic
Fine-silty	Gypsic			+15 to +22	Thermic	Isothermic
Fine-loamy	Carbonatic			>+22	Hyperthermic	Isohyperthermic
Etc.	Etc.					

[a]Skeletal refers to presence of 35–90% rock fragments by volume.
[b]Cation exchange activity class is not used for taxa already defined by low CEC (e.g., kandic or oxic groups).
[c]Permafrost present.
[d]Frigid is warmer in summer than cryic.

semiactive, or *subactive* with regard to their capacity to hold cations. For temperature classes, terms such as *cryic*, *mesic*, and *thermic* are used. The terms *shallow* and *micro* are sometimes used at the family level to indicate unusual soil depths.

Thus, a Typic Argiudoll from Iowa, USA, loamy in texture, having a mixture of moderately active clay minerals and with annual soil temperatures (at 50 cm depth) between 8 and 15 °C, is classed in the *loamy*, *mixed*, *active*, *mesic Typic Argiudolls* family. In contrast, a sandy-textured Typic Haplorthod, high in quartz, and located in a cold area in eastern Canada, is classed in the *sandy*, *siliceous*, *frigid Typic Haplorthods* family (note that clay activity classes are not used for soils in sandy textural classes).

Series

The series category is the most specific unit of the classification system. It is a subdivision of the family, and each series is defined by a specific range of soil properties involving primarily the kind, thickness, and arrangement of horizons. Features such as a hard pan within a certain distance below the surface, a distinct zone of calcium carbonate accumulation at a certain depth, or striking color characteristics may aid in series identification.

In many countries, each series is given a name, usually from some town, river, or lake such as Fargo, Muscatine, Cecil, Mohave, or Ontario.

The complete classification of a Mollisol, the Kokomo series, is given in Figure 3.47. This figure illustrates how *Soil Taxonomy* can be used to show the relationship between *the soil*,

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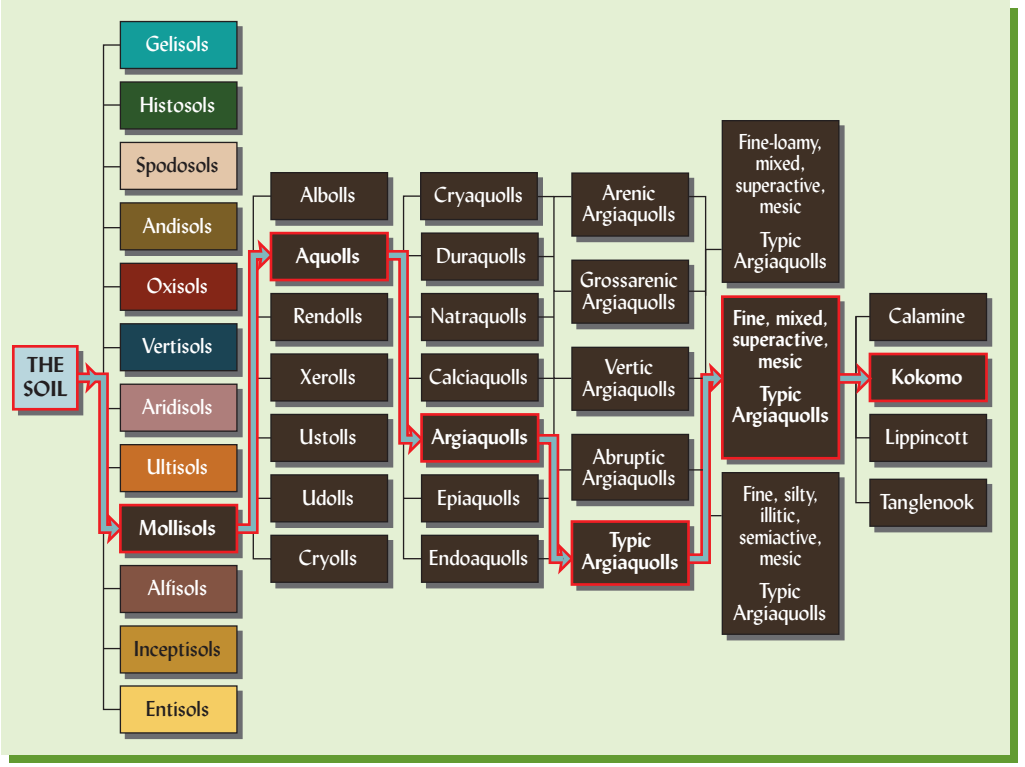

Figure 3.47 *How one soil (Kokomo) keys out in the overall classification scheme. The shaded boxes show that this soil is in the Mollisols order, Aquolls suborder, Argiaquolls great group, and so on. In each category, other classification units are shown in the order in which they key out in* Soil Taxonomy. *Many more families exist than are shown.* (Diagram courtesy of Ray R. Weil)

a comprehensive term covering all soils, and a specific soil series. The figure deserves study because it reveals much about the structure and use of *Soil Taxonomy*. If a soil series name is known, the complete *Soil Taxonomy* classification of the soil may be found on the Internet (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_053587). Box 3.3 illustrates how soil taxonomic information can assist in understanding the nature of a landscape such as shown in Figure 3.48.

BOX 3.3

USING SOIL TAXONOMY TO UNDERSTAND A LANDSCAPE

In real-world landscapes, different soils exist alongside each other, often in complex patterns. Adjacent soils on a tract of land may belong to different families, subgroups, great groups, or even different soil orders. Figure 3.48 depicts a landscape in a humid temperate region (Iowa) where 2–7 m of loess overlies leached glacial till and the native vegetation was principally tall grass prairie interspersed with small areas of trees. This landscape demonstrates how diagnostic horizons and other features of soil taxonomy are used to organize soils information. It also highlights the relationships among soils that allow us to make soil maps and interpret geographic soils information to help in planning projects on the land (see Chapter 19).

Seven soil map units are shown in the block landscape diagram, along with a profile diagram for the dominant soil series in each map unit. The soils include two Alfisols (Fayette and Downs) and five Mollisols (Tama, Wabash, Dinsdale, Muscatine, and Garwin). The particular set of soil horizons present in each profile relates to the (1) parent material, (2) vegetation, and (3) topography and drainage.

(continued)

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BOX 3.3

USING SOIL TAXONOMY TO UNDERSTAND A LANDSCAPE *(CONTINUED)*

Find the Dinsdale and Tama soils and notice where they occur in the landscape. The Dinsdale soil differs from the Tama because two parent materials (loess and glacial till) contributed to the Dinsdale profile, but the Tama soil is found where the loess layer by itself is thick enough to accommodate the entire profile. Both the Tama and Fayette soils exhibit argillic B horizons, but the Fayette has a thin ochric epipedon and a bleached albic horizon because it formed under forest vegetation, while the Tama has a thick mollic epipedon because it formed under grassland vegetation. The influence of topography can be seen by noting that soils on concave or level positions (the Garwin and Muscatine soils, which have slopes ranging from 0 to 1% and 1 to 3%, respectively) are wetter and less permeable than those on the steeper slopes (Tama and Dinsdale soils). In the less sloping, wetter soils, restricted drainage has retarded the development of an argillic horizon, so that only a gleyed (waterlogged) cambic B horizon (Bg) is present.

Are these relationships reflected in the soil taxonomy names? Note that the formative element aqu appears in the taxonomic name of the three wetter soils. Aqu appears at the suborder level (Endoaquolls) for the very wet, poorly drained soils, but only at the subgroup level for the less wet, somewhat poorly drained soil (Aquic Hapludoll). The formative element argi is used in the name of two soils (Argiudolls) to indicate that enough clay has accumulated in the B horizon of these Mollisols to develop into an argillic diagnostic horizon. Argi does not appear in the names of the two Alfisols, because an accumulation of clay (argillic or similar horizon) is a required feature of all Alfisols. Subgroup modifiers also provide important information about the interrelationships of these soils in the landscape. For example, the modifier Cumulic indicates that the Wabash soil has an unusually thick mollic epipedon because soil material washing off the uplands and carried by local streams has accumulated in the low-lying floodplains where this soil is found. The modifier Mollic used for the Downs soil indicates that this soil is transitional between the Alfisols and Mollisols, the A horizon in the Downs soils being slightly too thin to classify as a mollic epipedon.

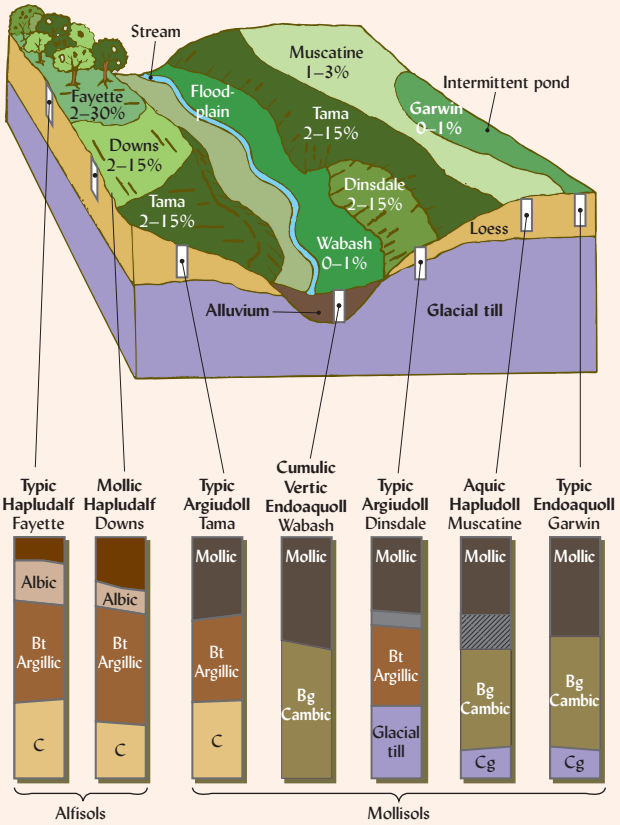

Figure 3.48 *Soil taxonomy reflects soil-landscape relationships.*

3.18 CONCLUSION

The soil that covers the Earth is actually comprised of many individual soils, each with distinctive properties. Among the most important of these properties are those associated with the layers, or *horizons*, found in a soil profile. These horizons reflect the physical, chemical, and biological processes soils have undergone during their development. Horizon properties greatly influence how soils can and should be used.

Knowledge of the kinds and properties of soils around the world is critical to humanity's struggle for survival and well-being. A soil classification system based on these properties is equally critical if we expect to use knowledge gained at one location to solve problems at other locations where similarly classed soils are found. *Soil Taxonomy*, a classification system based on measurable soil properties, helps fill this need in more than 50 countries. Scientists constantly update the system as they learn more about the nature and properties of the world's soils and the relationships among them. The updates are published online periodically as new editions of *Keys to Soil Taxonomy* (http://www.nrcs.usda.gov/wps/

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portal/nrcs/main/soils/survey/class/). In the remaining chapters of this book we will use *Soil Taxonomy* names whenever appropriate to indicate the kinds of soils to which a concept or illustration may apply.

STUDY QUESTIONS

1. Diagnostic horizons are used to classify soils in *Soil Taxonomy*. Explain the difference between a diagnostic horizon (such as an argillic horizon) and a genetic horizon designation (such as a Bt1 horizon). Give a field example of a diagnostic horizon that contains several genetic horizon designations.
2. Explain the relationships among a *soil individual*, a *polypedon*, a *pedon*, and a *landscape*.
3. Rearrange the following soil orders from the *least* to the *most* highly weathered: Oxisols, Alfisols, Mollisols, Entisols, and Inceptisols.
4. What is the principal soil property by which Ultisols differ from Alfisols? Inceptisols from Entisols?
5. Use the key given in Figure 3.11 to determine the soil order of a soil with the following characteristics: a spodic horizon at 30 cm depth; permafrost at 80 cm depth. Explain your choice of soil order.
6. Of the five soil-forming factors discussed in Chapter 2 (parent material, climate, organisms, topography, and time), choose *two* that have had the dominant influence on developing soil properties characterizing each of the following soil orders: Vertisols, Mollisols, Spodosols, and Oxisols.
7. To which soil order does each of the following belong: Psamments, Udolls, Argids, Udepts, Fragiudalfs, Haplustox, and Calciusterts.
8. What's in a name? Write a hypothetical soil profile description and land-use suitability interpretation for a hypothetical soil that is classified in the Aquic Argixerolls subgroup.
9. Explain why *Soil Taxonomy* is said to be a hierarchical classification system.
10. Name the soil taxonomy category and discuss the engineering implications of these soil taxonomy classes: Aquic Paleudults, Fragiudults, Haplusterts, Saprists, and Turbels.

REFERENCES

Arnold, R., S. Shoba, P. Krasilnikov, and J. J. I. I. Marti. 2012. *A Handbook of Soil Terminology, Correlation and Classification*. Earthscan, London. 448 p.

Barrera-Bassols, N., J. Alfred Zinck, and E. Van Ranst. 2006. "Symbolism, knowledge and management of soil and land resources in indigenous communities: Ethnopedology at global, regional and local scales," *Catena*, **65**:118–137.

Coulombe, C. E., L. P. Wilding, and J. B. Dixon. 1996. "Overview of vertisols: Characteristics and impacts on society," *Adv.Agron.*, **17**:289–375.

Ditzler, C. A. 2005. "Has the polypedon's time come and gone?" *HPSSS Newsletter*, February 2005, pp. 8–11. Commission on History, Philosophy and Sociology of Soil Science, International Union of Soil Sciences. http://www.iuss.org/Newsletter12C4-5.pdf (verified 20 October 2005).

Eswaran, H. 1993. "Assessment of global resources: Current status and future needs," *Pedologie*, **43**(1):19–39.

Eswaran, H., T. Rice, R. Ahrens, and B. A. Stewart (eds.). 2003. *Soil Classification: A Global Desk Reference*. CRC Press, Boca Raton, FL.

Gong, Z., X. Zhang, J. Chen, and G. Zhang. 2003. "Origin and development of soil science in ancient China," *Geoderma*, **115**:3–13.

Lin, H. 2011. "Three principles of soil change and pedogenesis in time and space," *Soil Sci. Soc. Am. J.*, **75**:2049–2070.

Riecken, F. F., and G. D. Smith. 1949. "Principal upland soils of Iowa, their occurrence and important properties," *Agron*, **49** (revised). Iowa Agr. Exp. Sta.

Shaw, J. N., L. T. West, D. E. Radcliffe, and D. D. Bosch. 2000. "Preferential flow and pedotransfer functions for transport properties in sandy Kandiustults," *Soil Sci. Soc. Am. J.*, **64**:670–678.

Soil Survey Staff. 1975. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Natural Resources Conservation Service, Washington, DC.

Soil Survey Staff. 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. 2nd ed. Natural Resources Conservation Service, Washington, DC.

Soil Survey Staff. 2014. *Keys to Soil Taxonomy.* 12th ed. [Online]. Available by United States Department of Agriculture, Natural Resources Conservation Service http://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1252094&ext=pdf.

SSSA. 1984. *Soil Taxonomy, Achievements and Challenges*. SSSA Special Publication 14. Soil Sci. Soc. Am., Madison, WI.

Talawar, S., and R. E. Rhoades. 1998. "Scientific and local classification and management of soils," *Agric. Human Values.*, **15**:3–14.

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4 Soil Architecture and Physical Properties

And when that crop grew, and was harvested, no man had crumbled a hot clod in his fingers and let the earth sift past his fingertips.
—*John Steinbeck*, The Grapes of Wrath

Structure and texture of a Mollisol. (Ray R. Weil)

Soil physical properties profoundly influence how soils function in an ecosystem and how they can best be managed. Success or failure of both agricultural and engineering projects often hinges on the physical properties of the soil used. The occurrence and growth of many plant species are closely related to soil physical properties, as is the movement over and through soils of water and its dissolved nutrients and chemical pollutants.

Soil scientists use the color, texture, and other physical properties of soil horizons in classifying soil profiles and in making determinations about soil suitability for various types of land uses. Knowledge of basic soil physical properties is not only of great practical value in itself, but will also help in understanding many aspects of soils considered in later chapters.

The term *soil architecture* used in the title of this chapter encourages us to think of the soil as an edifice, as if it were a building such as a house. The primary particles in soil are the building blocks from which the house is constructed. **Soil texture** describes the sizes of the soil particles. The larger mineral particles usually are embedded in, and coated with, clay and other colloidal size materials. Where the larger mineral particles predominate, the soil is gravelly or sandy; where the mineral colloids are dominant, the soil is claylike. All gradations between these extremes are found in nature.

Soil structure describes the manner in which soil particles are aggregated. This property, therefore, defines the nature of the system of pores and channels in a soil.

The physical properties considered in this chapter focus on soil solids and on the pore spaces between the solid particles. Together, soil texture and structure help determine the ability of the soil to hold and conduct the water and air necessary for sustaining life. These factors also determine how soils behave when used for highways and building foundations, or when manipulated by tillage. In fact, through their influence on the movement of water through and off soils, physical properties also exert considerable control over the destruction of the soil itself by erosion.

4.1 SOIL COLOR[1]

Color is often the most obvious characteristic of a soil. Although color itself has little effect on the behavior and use of soils, it does provide clues about other soil properties and conditions. To obtain the precise, repeatable description of colors needed for soil

[1]For a collection of papers on causes and measurement of soil color, see Bigham and Ciolkosz (1993).

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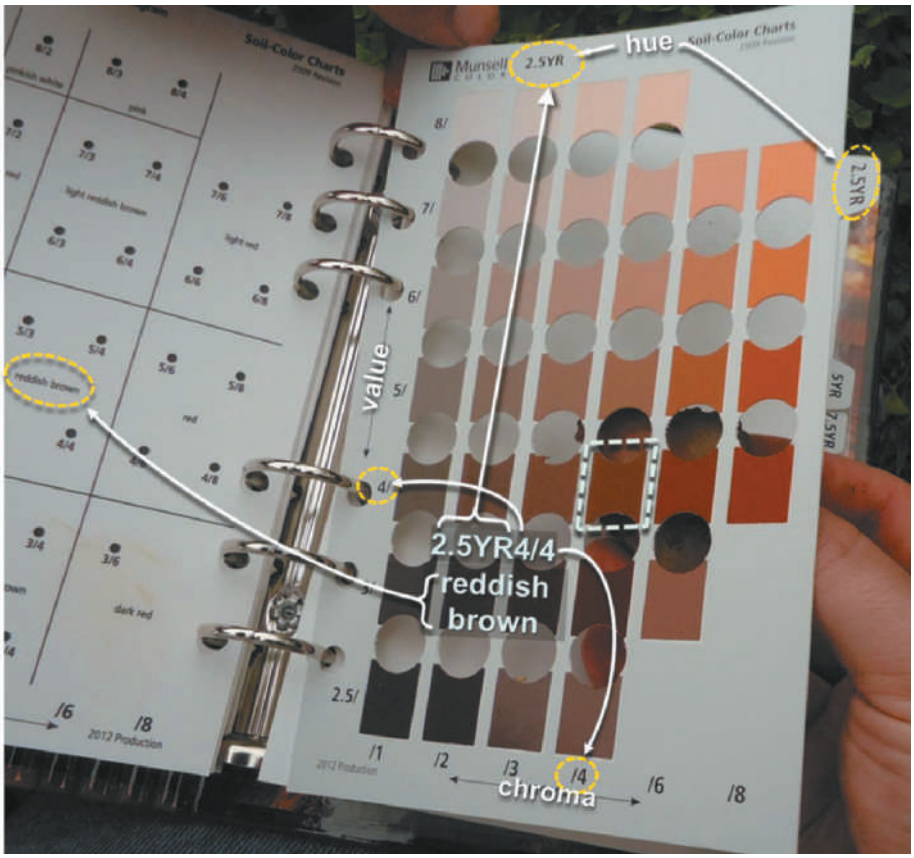

Figure 4.1 *A page from the Munsell color book showing the colors of 2.5YR Hue present in soils. The color of the soil clod being held behind the page is closest to outlined color chip designated 2.5YR4/4. The 2.5YR stands for the hue or pigment (reddish brown), the 4/ indicates the degree of lightness or darkness, going from near black of low values near the bottom of the page to near-white of high values near the top. The /4 designates the chroma column or brightness of the color, going from near grayscale at the spine of the book very bright intense colors near the outer edge of the page. The color name "reddish brown" is applied to a group of four color chips as shown on the facing page (left).*
(Photo courtesy of Ray R. Weil)

classification and interpretation, soil scientists compare a small piece of soil to standard color chips in special Munsell[2] color charts. The Munsell charts use color chips arranged according to the three components of how people see color: the **hue** (in soils, usually redness or yellowness), the **value** (lightness or darkness, a value of 0 being black), and the **chroma** (intensity or brightness, a chroma of 0 being neutral gray). In a Munsell color book (carefully study Figure 4.1), color chips are arranged on pages with values increasing from the bottom to the top, and the chromas increasing from left to right, while hues change from one page to another.

Soils display a wide range of reds, browns, yellows, and even greens (Figure 4.2). Some soils are nearly black, others nearly white. Some soil colors are very bright, others are dull grays. Soil colors may vary from place to place in the landscape (see catena in Figure 2.34) as well as with depth through the various layers (horizons) within a soil profile (see Figure 3.34), or even within a single horizon or clod of soil (Figure 4.2). When making field soil descriptions, it is worth noting that horizons in a given profile that differ in chroma and value are often similar in hue.

Causes and Interpretation of Soil Colors

Three major factors influence soil colors: (1) organic matter content, (2) water content, and (3) the presence and oxidation states of iron and manganese oxides in various minerals. Organic matter tends to coat mineral particles, darkening and masking the brighter colors of the minerals themselves (see Figures 3.33 and 4.3). Soils are generally darker (have low color value) when wet than when dry (Figure 4.4). Water content has a more profound indirect

[2]Developed in 1905 by artist Albert Munsell to explain colors to his art students, the Munsell system is now also used to standardize colors in a wide range of scientific and commercial applications.

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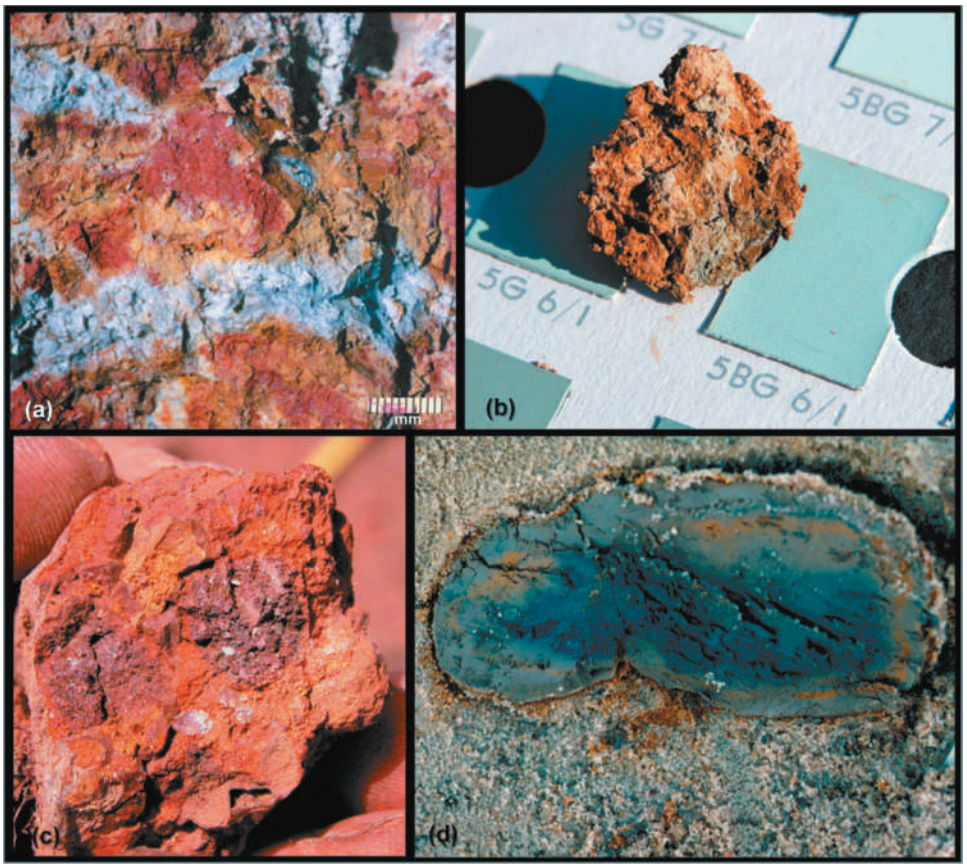

Figure 4.2 *Examples of some red, orange, brown, gray, and blue soil colors derived from various iron minerals and influenced by oxidation state. Scale marked in mm. (a) B horizon peds in an Ultisol in Alabama, USA, where the interped cracks often hold stagnant water have turned gray, while the ped interiors have remained oxidized and are red and yellow. (b) B horizon ped in an Alfisol in Maryland, USA, showing bluish color where a plant root has used up the oxygen and created localized reducing conditions. (c) A ped from the B horizon of an Alfisol on Chad showing purplish hardened plinthite. (d) A clay inclusion in sandy river bank sediment along the Chesapeake Bay in Maryland, USA, showing blue and gray colors where iron has become reduced.* (Photos courtesy of Ray R. Weil)

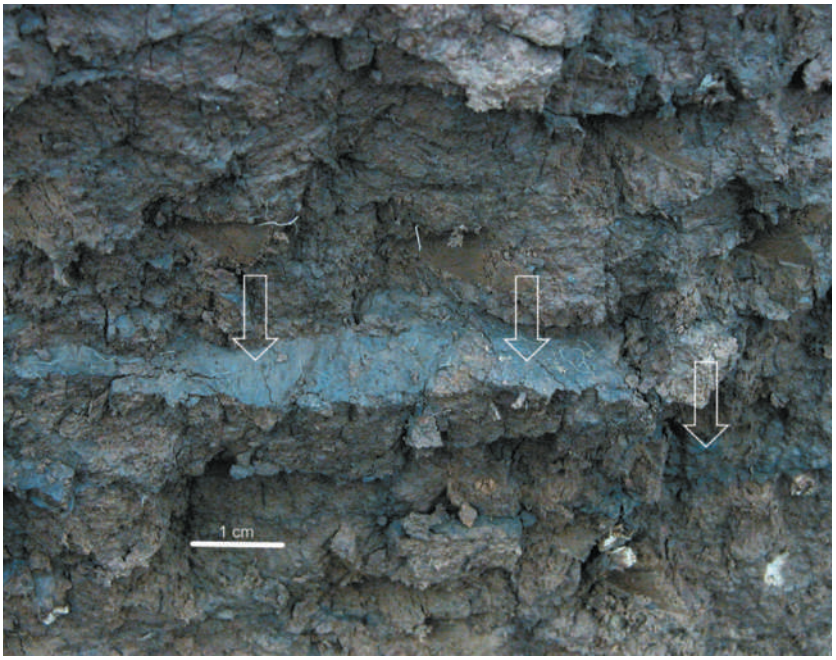

Figure 4.3 *Black organic matter coating on peds in the B horizon of a Kansas Mollisol.* (Photo courtesy of Ray R. Weil)

effect on soil colors. It influences the level of oxygen in the soil, and thereby the rate of organic matter accumulation which darkens the soil. Water also affects the oxidation state of iron and manganese. In well-drained uplands, especially in warm climates, well-oxidized iron compounds impart bright (high chroma) reds and browns to the soil. Other minerals that

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Figure 4.4 *The effect of water content on soil color. The right side of this profile was sprayed with water.* (Photo courtesy of Ray R. Weil)

Figure 4.5 *Greenish colored clay in a Marlton soil Bss horizon and blackish coatings from manganese oxides in a Davidson soil B/C horizon.* (Photos courtesy of Ray R. Weil)

influence soil color include manganese oxide (black) and glauconite (green)—as in Figure 4.5. In dry regions, calcite and soluble salts impart a whitish color to many soils. These colors are in contrast to the gray and bluish colors (low chroma) that reduced iron compounds impart to poorly drained soil profiles (Figure 4.2*b*,*d*). Under prolonged anaerobic conditions, reduced iron (which is far more soluble than oxidized iron) is removed from particle coatings, often exposing the light gray colors of the underlying silicate minerals. Soil exhibiting gray colors from reduced iron and iron depletion is said to be **gleyed** (Figure 4.6). If sulfur is present under anaerobic conditions, iron sulfides may color the soil black regardless of the organic matter level.

Color is used as a diagnostic criterion for classifying soils. For example, a mollic epipedon (see Section 3.2) is so dark that both its value and its chroma are 3 or less. In another example, Rhodic subgroups of certain soil orders have B horizons that are very red, having hues between 2.5YR (the most red of the yellowish red pages) and 10R (the most red in the Munsell color book). The presence in upper horizons of gley (low-chroma colors), either alone or mixed in a mottled pattern with brighter colors (see Figure 4.6), is used in delineating **wetlands**, for it is indicative of waterlogged conditions during at least a major part of the plant growing season (see Section 7.7). The depth in the profile at which gley colors are found helps to define the **drainage class** of the soil (see Figure 19.3).

Finally, it is worth mentioning that soils, with their distinctive colors, are important aesthetic components of the landscape. For example, warm, reddish colors are characteristic of many tropical and subtropical landscapes, while dark grays and browns typify cooler, more temperate regions.

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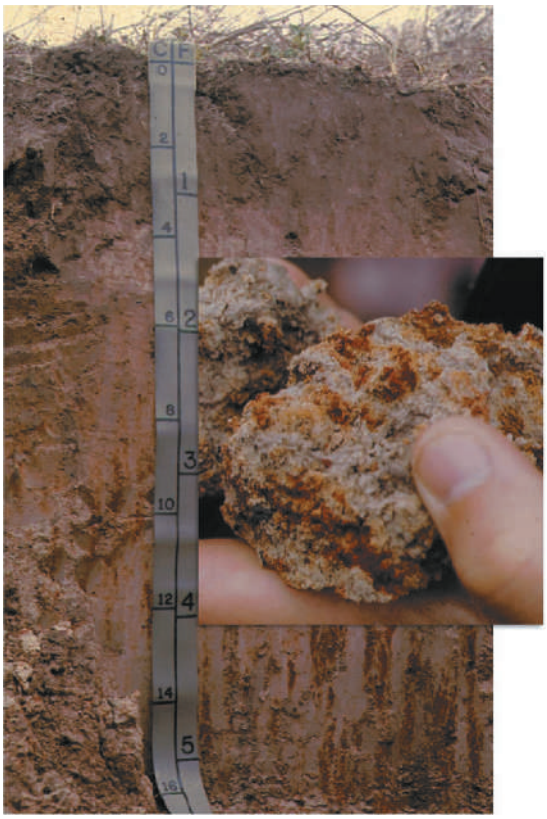

Figure 4.6 *Gleyed subsoil horizons in a Plinthaqualf from Texas, USA, showing the gray colors associated with reduced iron as well as areas of reddish colors associated with concentrations of oxidized iron.* (Photos courtesy of Ray R. Weil)

4.2 SOIL TEXTURE (SIZE DISTRIBUTION OF SOIL PARTICLES)

Knowledge of the proportions of different-sized particles in a soil (i.e., the **soil texture**) is critical for understanding soil behavior and management. When investigating soils on a site, the texture of various soil horizons is often the first and most important property to determine, for a soil scientist can draw many conclusions from this information. Furthermore, the texture of a soil in the field is not readily subject to change, so it is considered a basic permanent property of a soil.

Nature of Soil Separates

Diameters of individual soil particles range over six orders of magnitude, from boulders (1 m) to submicroscopic clays ($<10^{-6}$ m). Scientists group these particles into soil **separates** according to several classification systems, as shown in Figure 4.7. The classification system established by the U.S. Department of Agriculture is used in this text. The size ranges for these separates are not purely arbitrary, but reflect major changes in how the particles behave and in the physical properties they impart to soils.

Gravels, cobbles, boulders, and other coarse fragments greater than 2 mm in diameter may affect the behavior of a soil, but they are not considered to be part of the **fine earth fraction** to which the term *soil texture* properly applies.

Sand. Particles smaller than 2 mm but larger than 0.05 mm are termed *sand*. Sand feels gritty between the fingers. The particles are generally visible to the naked eye and may be rounded or angular (Figure 4.8), depending on the degree of weathering and abrasion undergone. Coarse sand particles may be rock fragments containing several minerals, but most sand grains consist of a single mineral, usually quartz (SiO_2) or other primary silicate minerals (Figure 4.9). Because of the dominance of quartz, the sand separate generally contains few

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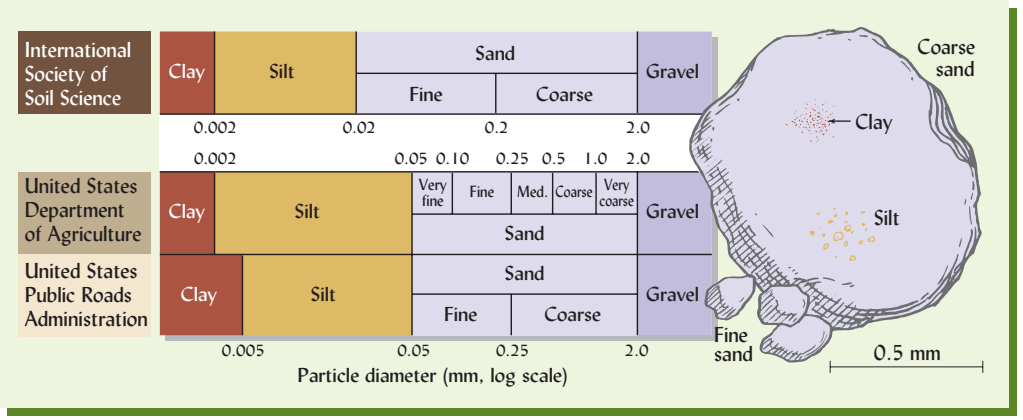

Figure 4.7 *Classification of soil particles according to their size. The shaded scale in the center and the names on the drawings of particles follow the U.S. Department of Agriculture system, which is widely used throughout the world and in this book. The other two systems shown are also widely used by soil scientists and by highway construction engineers. The drawing illustrates the sizes of soil separates (note scale).* (Diagram courtesy of Ray R. Weil)

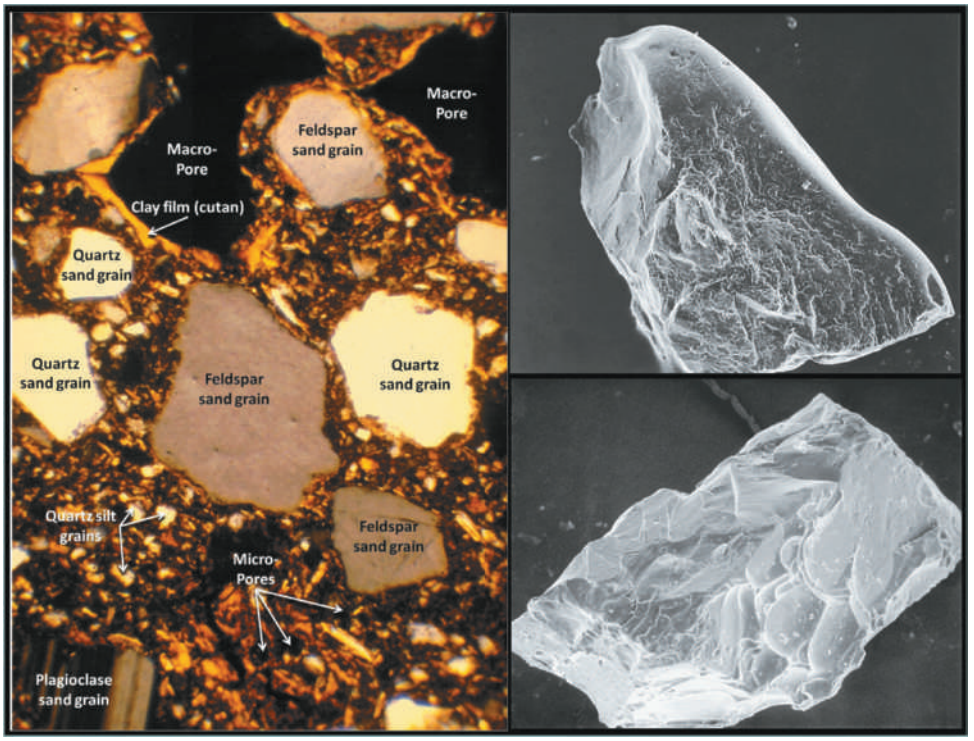

Figure 4.8 (Left) *A thin section of a loamy soil as seen through a microscope using polarized light (empty pores appear black). The sand and silt particles shown are irregular in size and shape, the silt being only smaller. Although quartz dominates the sand and silt fractions in this soil, several other silicate minerals can be seen (plagioclase, feldspar). Clay films coat the walls of the large pores (arrows). Scanning electron micrographs of sand grains show quartz sand (bottom right) and a feldspar grain (upper right) magnified about 40 times.* (Left photo courtesy of Martin Rabenhorst, University of Maryland; right photos courtesy of J. Reed Glasmann, Union Oil Research)

plant nutrients. The large particle size means that whatever nutrients are present will not likely be released for plant uptake.

As sand particles are relatively large, so, too, the pores between them are relatively large. The large pores in sandy soils cannot hold water against the pull of gravity (see Section 5.2) and so drain rapidly and promote entry of air into the soil. The relationship between particle size and **specific surface area** (the surface area for a given mass of particles) is illustrated in Figure 4.10. The large particles of sand have low specific surface areas. Therefore, sand particles possess little capacity to hold water or nutrients and do not stick together into a coherent mass (see Section 4.9). Owing to the just described properties, most sandy soils are well aerated and loose, but also infertile and prone to drought.

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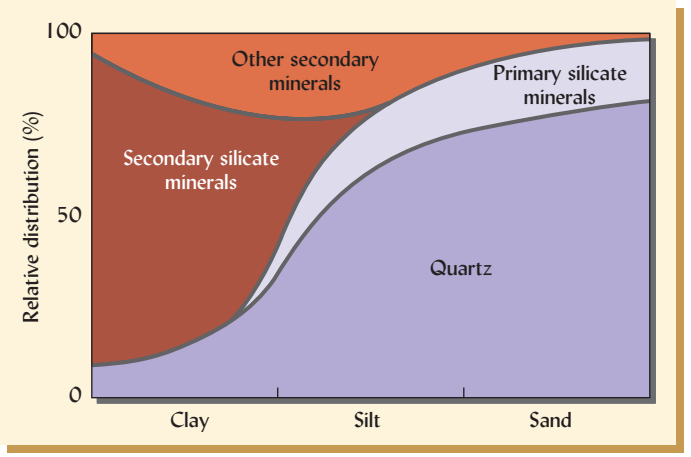

Figure 4.9 *General relationship between particle size and kinds of minerals present. Quartz dominates the sand and coarse silt fractions. Primary silicates such as the feldspars, hornblende, and micas are present in the sands and, in decreasing amounts, in the silt fraction. Secondary silicates dominate the fine clay. Other secondary minerals, such as the oxides of iron and aluminum, are prominent in the fine silt and coarse clay fractions.* (Diagram courtesy of N. Brady)

Silt. Particles smaller than 0.05 mm but larger than 0.002 mm in diameter are classified as *silt*. Although similar to sand in shape and mineral composition, individual silt particles are so small as to be invisible to the unaided eye (see Figure 4.7). Rather than feeling gritty when rubbed between the fingers, silt feels smooth or silky, like flour. Where silt is composed of weatherable minerals, the relatively small size (and large surface area) of the particles allows weathering rapid enough to release significant amounts of plant nutrients.

The pores between particles in silty material are much smaller (and much more numerous) than those in sand, so silt retains water and lets less drain through. However, even when wet, silt itself does not exhibit much **stickiness** or **plasticity** (malleability). What little plasticity, cohesion, and adsorptive capacity some silt fractions exhibit is largely due to a film of adhering clay (see Figure 2.21). Because of their low stickiness and plasticity, soils high in silt and fine sand can be highly susceptible to erosion by both wind and water. Silty soil is easily washed away by flowing water in a process called **piping** (Box 4.1).

Clay. Clay particles are smaller than 0.002 mm. They therefore have very large specific surface areas, giving them a tremendous capacity to adsorb water and other substances. A spoonful of clay may have a surface area the size of a football field (see Section 8.1). This large adsorptive surface causes clay particles to cohere in a hard mass after drying. When wet, clay is sticky and can be easily molded (exhibits high plasticity).

Fine clay–sized particles are so small that they behave as **colloids**—if suspended in water they do not readily settle out. Unlike most sand and silt particles, clay particles tend

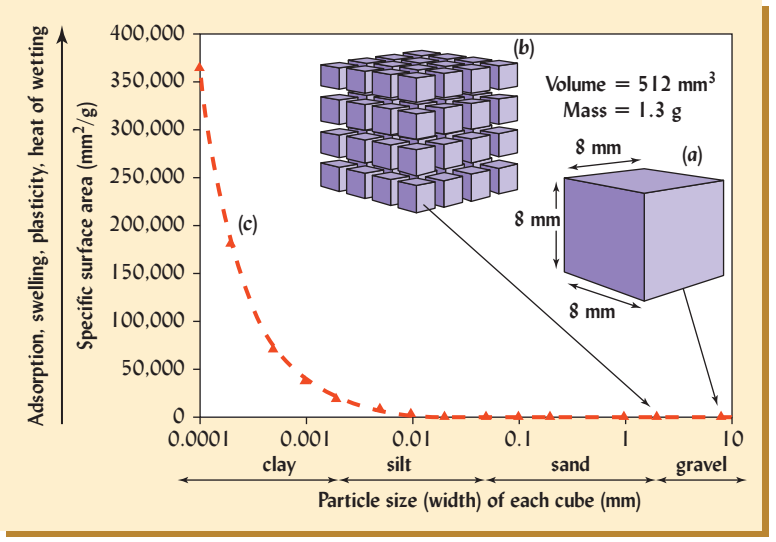

Figure 4.10 *Surface area and particle size. Consider a 1.3 g cube 8 mm on a side* (a). *The cube has six faces with a total of 384 mm² surface area (6 faces • 64 mm² per face) or a specific surface of 295 mm²/g (384/1.3). If this cube were cut into smaller cubes of only 2 mm on each side* (b), *the same mass would now be present as 64 (4 • 4 • 4) cubes, each with 24 mm² of surface area (6 faces • 4 mm² per face) for a total surface area of 1536 mm² (24 mm² per cube • 64 cubes), or a specific surface of 1182 mm²/g (1536/1.3). This is four times as much surface area as the single large cube. The curve* (c) *explains why nearly all of the adsorbing power, swelling, plasticity, heat of wetting, and other surface area–related properties are associated with the clay fraction in mineral soils.* (Diagram courtesy of Ray R. Weil)

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BOX 4.1

SILT AND THE FAILURE OF THE TETON DAM[a]

One of the most tragic and costly engineering failures in American history occurred in southern Idaho on 5 June 1976, less than a year after construction was completed on a large earth-filled dam across the Teton River. Eleven people were killed and 25,000 made homeless in the five hours it took to empty the 28-km-long lake that had been held in place by the dam. Some $400 million (1976 dollars) worth of damages were caused as the massive wall of water surged through the collapsed dam and the valley below. The dam failed with little warning as small seepage leaks (Figure 4.11, left) quickly turned into raging torrents that swept away a team of bulldozers sent to make repairs.

The Teton dam was built according to a standard, time-tested design for zoned earth-fill embankments (Figure 4.12). Essentially, after preparing a base in the rhyolitic/basaltic rock below the soil, a core (zone 1) of tightly compacted soil material was constructed and covered with a layer (zone 2) of rocks and coarser alluvial soil material to protect it from water and wind erosion.

The core is meant to be the watertight seal that prevents water from seeping through the dam. Normally, clayey material is chosen for the core, since the sticky, plastic qualities of moist clay allow it to be compacted into a malleable, watertight mass that holds together and does not crack so long as it is kept moist. Silt, on the other hand, though it may appear similar to clay in the field, has little or no stickiness or plasticity and therefore cannot be compacted into a coherent mass as clay can. In fact, a moist mass of compacted silt will crack as it settles because it lacks plasticity. If water seeps into these cracks, the silty material will rapidly wash away with the flowing water, enlarging the crack and inviting more water to flow through, which will wash away still more of the silt. This process of rapidly enlarging seepage channels is termed ***piping***. Such piping was almost certainly a major cause of the Teton Dam failure, for the engineers built the zone 1 core of the dam using the local windblown silt deposits (termed ***loess***—see Section 2.3) rather than clay.

This was a tragic but useful lesson about the role of texture in determining soil behavior and the importance of distinguishing clay from silt.

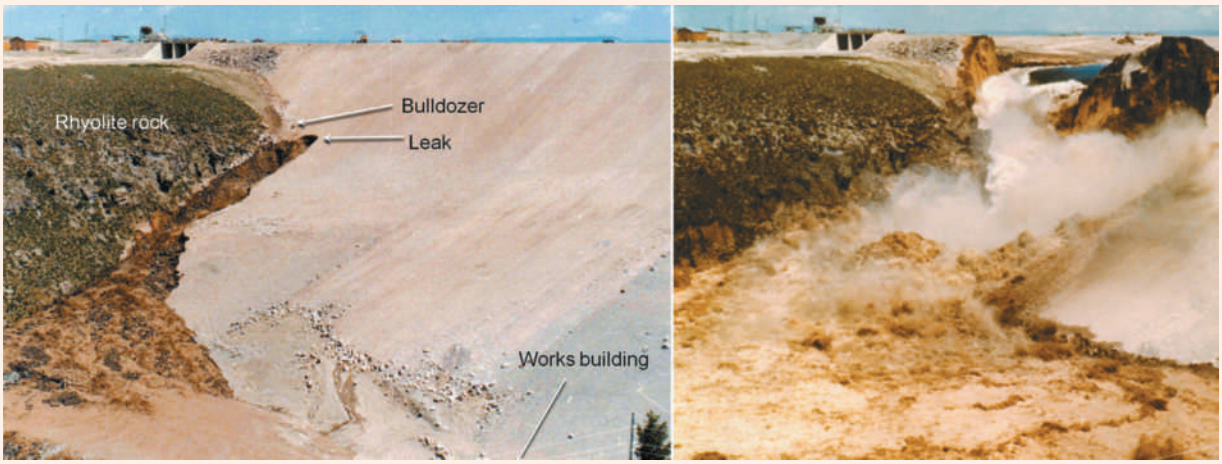

Figure 4.11 *Photographs taken less than two hours apart show how two leaks in the dam rapidly enlarged, leading the complete collapse and failure of Teton Dam.* (Left) *Black rhyolitic and basaltic rocks form the abutments on either side of the dam. Dark brown muddy water can be seen leaking from the left side of the dam near the black rhyolitic rock abutment. The elongated speck above the leak is a large bulldozer attempting to push material down to plug the hole. This and another dozer were soon swallowed by the rapidly enlarging leak.* (Right) *Total collapse of the dam allowed a torrent of water to rush out, emptying the entire lake in just a few hours, leaving a path of destruction downstream.* (Photos courtesy of U.S. Bureau of Land Reclamation)

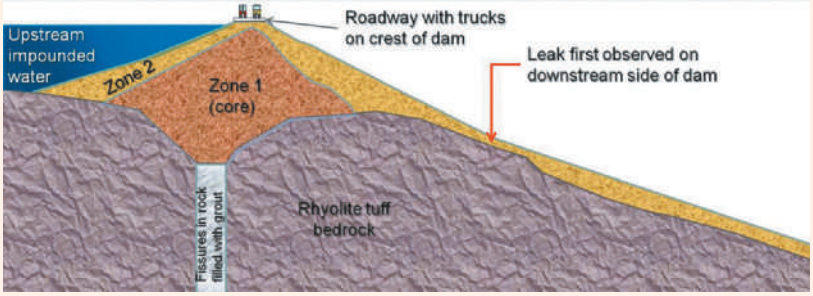

Figure 4.12 *Generalized diagram of the zoned design of the dam built across the Teton River.* (Diagram courtesy of Ray R. Weil)

[a]Based, in part, on Arthur (1977) and Sasiharan (2003).

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to be shaped like tiny flakes or flat platelets. The pores between clay particles are very small and convoluted, so movement of both water and air is very slow. In clayey soil, the pores between particles are tiny in size, but huge in number, allowing the soil to hold a great deal of water; however, much of it may be unavailable to plants (see Section 5.9). Each unique clay mineral (see Chapter 8) imparts different properties to the soils in which it is prominent. Therefore, soil properties such as shrink–swell behavior, plasticity, water-holding capacity, soil strength, and chemical adsorption depend on the *kind* of clay present as well as the *amount*.

Influence of Surface Area on Other Soil Properties

When particle size decreases, specific surface area and related properties increase greatly, as shown graphically in Figure 4.10. Fine colloidal clay has about 10,000 times as much surface area as the same weight of medium-sized sand. Soil texture influences many other soil properties in far-reaching ways (see Table 4.1) as a result of five fundamental surface phenomena:

1. In addition to the tiny pools of water held in the smaller soil pores, water is also retained in soils as thin films on the surfaces of soil particles. The greater the surface area, the greater the soil's capacity for holding water films.
2. Both gases and dissolved chemicals are attracted to and adsorbed by mineral particle surfaces. The greater the surface area, the greater the soil's capacity to retain nutrients and other chemicals.
3. Weathering takes place at the surface of mineral particles, releasing constituent elements into the soil solution. The greater the surface area, the greater the rate of release of plant nutrients from weatherable minerals.
4. The surfaces of mineral particles often carry both negative and some positive electromagnetic charges so that particle surfaces and the water films between them tend to attract each other (see Section 4.5). The greater the surface area, the greater the propensity for soil particles to stick together in a coherent mass, or as discrete aggregates.
5. Microorganisms tend to grow on and colonize particle surfaces. For this and other reasons, microbial reactions in soils are greatly affected by the specific surface area.

Table 4.1
GENERALIZED INFLUENCE OF SOIL SEPARATES ON SOME PROPERTIES AND BEHAVIOR OF SOILS[a]

	Rating associated with soil separates		
Property/behavior	***Sand***	***Silt***	***Clay***
Water-holding capacity	Low	Medium to high	High
Aeration	Good	Medium	Poor
Drainage rate	High	Slow to medium	Very slow
Soil organic matter level	Low	Medium to high	High to medium
Decomposition of organic matter	Rapid	Moderate	Slow
Warm-up in spring	Rapid	Moderate	Slow
Compactability	Low	Medium	High
Susceptibility to wind erosion	Moderate (high if fine sand)	High	Low
Susceptibility to water erosion	Low (unless fine sand)	High	Low if aggregated, high if not
Shrink–swell potential	Very low	Low	Moderate to very high
Sealing of ponds, dams, and landfills	Poor	Poor	Good
Suitability for tillage after rain	Good	Medium	Poor
Pollutant leaching potential	High	Medium	Low (unless cracked)
Ability to store plant nutrients	Poor	Medium to high	High
Resistance to pH change	Low	Medium	High

[a]Exceptions to these generalizations do occur, especially as a result of soil structure and clay mineralogy.

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4.3 SOIL TEXTURAL CLASSES

Within the three broad groups of *sandy soils*, *clayey soils*, and *loamy soils*, specific **textural class** names convey a more precise idea of the size distribution of particles and the general nature of soil physical properties. The relationship between textural class names and proportions of sand, silt, and clay is commonly shown diagrammatically as a triangular graph (Figure 4.13). It is worthwhile to study Figure 4.13 carefully and learn how to use the **textural triangle** by following the examples given in the caption.

The 14 textural classes named in Table 4.2 form a graduated sequence from the sands, which are coarse in texture to the clays, which are fine. Sands and loamy sands are dominated by the properties of sand, for the sand separate comprises at least 70% of the material by weight and less than 15% of the material is clay (see boundaries on Figure 4.13). Clays, sandy clays, and silty clays are dominated by characteristics of clay. Likewise, silts are dominated by the properties of silt. However, most soils are some type of **loam**.

Loams. A **loam** is a mixture of sand, silt, and clay particles that exhibits the *properties* of those separates in about equal proportions. This definition does not mean that the three separates are present in equal *amounts* (that is why the loam class is not exactly in the middle of the triangle in Figure 4.13). This anomaly exists because a relatively small percentage of clay is required to engender clayey properties in a soil, whereas small amounts of sand and silt have a lesser influence on how a soil behaves. A loam in which sand is dominant is classified as a *sandy loam.* In the same way, some soils are classed as *silt loams*, *silty clay loams*, *sandy clay loams*, and *clay loams*. Note from Figure 4.13 that a *clay loam* may have as little as 26% clay, but to qualify as *sandy loam* or *silt loam*, a soil must have at least 45% sand or 50% silt, respectively.

Coarse Fragment Modifiers. If a soil contains a significant proportion of particles larger than sand (termed **coarse fragments**), a qualifying adjective may be used as part of the textural class name. Coarse fragments that range from 2 to 75 mm along their greatest diameter are termed *gravel* or *pebbles,* those ranging from 75 to 250 mm are called *cobbles* (if round) or

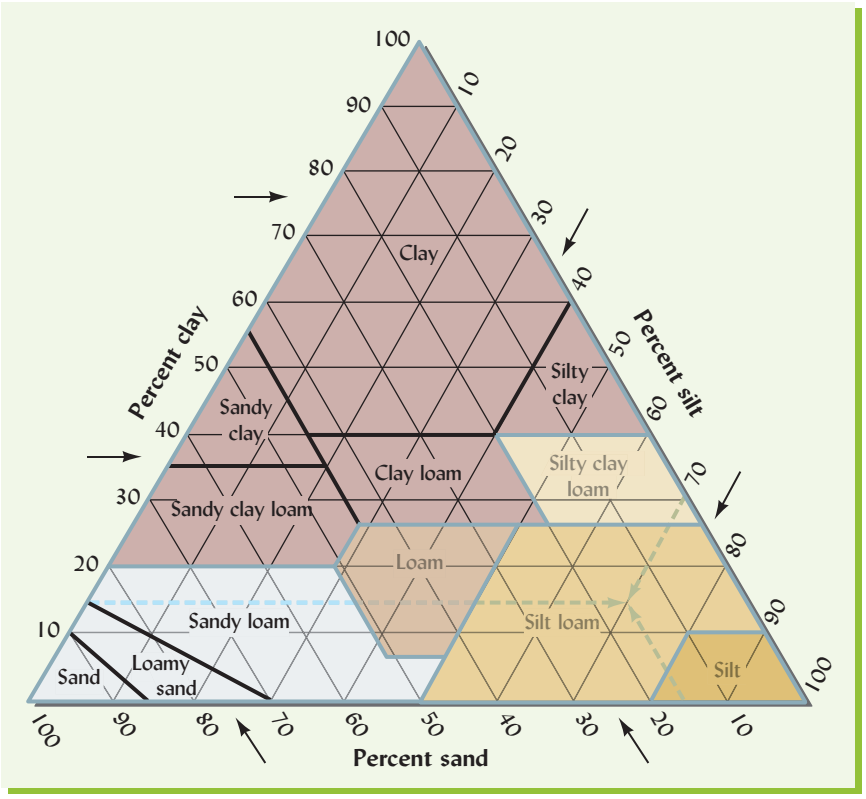

Figure 4.13 *Soil textural classes are defined by percentages (g/100 g mineral soil) of sand, silt, and clay according to the heavy boundary lines on the textural triangle. To use the graph, first find the appropriate clay percentage along the left side of the triangle, then draw a line inward parallel to the base of the triangle. Next find the sand percentage along the base of the triangle and draw a line inward parallel to the right side of the triangle. The small arrows indicate the direction to draw the lines. The name of the compartment in which these two lines intersect indicates the textural class of the soil sample. If all three percentages are used, the three lines will all intersect at the same point. Because the percentages for sand, silt, and clay add up to 100%, the third percentage can easily be calculated if the other two are known. For example, a soil that contains15% sand, 15% clay, and 70% silt is a "Silt loam" (red dashed lines). Lines (not shown) for another soil sample with 33% sand, 34% silt, and 33% clay would intersect in the center of the "Clay loam".*

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Table 4.2
General Terms Used to Describe Soil Texture in Relation to the Basic Soil Textural Class Names in the U.S. Department of Agriculture Classification System

Basic soil textural class names													
Sands	Loamy sands	Sandy loam	Fine sandy loam[a]	Very fine sandy loam[a]	Loam	Silt loam	Silt	Sandy clay loam	Silty clay loam	Clay loam	Sandy clay	Silty clay	Clay
General texture terms													
----- Coarse -----		-- Moderately -- coarse		---------- Medium ----------				--- Moderately fine ---			---------- Fine ----------		
Sandy soils		---------- Loamy soils ----------									----- Clayey soils -----		

[a]Although not included as class names in Figure 4.13, these soils are usually treated separately because of their fine sand content.

channers (if flat), and those more than 250 mm across are called *stones* or *boulders.* A *gravelly*, *fine sandy loam* is an example of such a modified textural class.

Alteration of Soil Textural Class

Over long periods of time, pedologic processes (see Chapter 2) such as illuviation and mineral weathering can alter the textures of certain soil horizons. Likewise, erosion and subsequent deposition downslope can selectively remove or deposit particles of certain sizes. However, management practices generally do not alter the textural class of a soil on a field scale. Changing the texture of a given soil would require mixing it with another soil material of a different textural class. For example, the incorporation of large quantities of sand to change the physical properties of a clayey soil for use in greenhouse pots or for turf grass would be considered to change the soil texture. However, adding peat or compost to a soil while mixing a potting medium does not constitute a change in texture, since the property of texture refers only to the mineral particles. In fact, the term *soil texture* is not relevant to artificial media that contain mainly perlite, peat, styrofoam, or other nonsoil materials.

Great care must be exercised in attempting to ameliorate physical properties of fine-textured soils by adding sand. Where specifications (as for a landscape design) call for soil materials of a certain textural class, it is generally advisable to find a naturally occurring soil that meets the specification, rather than attempt to alter the textural class by mixing in sand or clay. If the sand is not of the proper size and not added in sufficient amounts, it may make matters worse, rather than better. While adjacent coarse sand grains form large pores between them, sand grains embedded in a silty or clayey matrix do not. Mixing in moderate amounts of fine sand or sand ranging widely in size may yield a product more akin to concrete than to a sandy soil. For some applications (such as golf putting greens and athletic fields), the need for rapid drainage and resistance to compaction even when wet may justify the construction of an artificial soil from carefully selected uniform sands. Similarly, where a smooth, hard surface is required, such as for a tennis court, an artificial clay soil may be needed.

Determination of Textural Class by the "Feel" Method

Textural class determination is one of the first field skills a soil scientist should develop. Determining the textural class of a soil by its feel is of great practical value in soil survey, land classification, and any investigation in which soil texture may play a role. Accuracy depends largely on experience, so practice whenever you can, beginning with soils of known texture to "calibrate" your fingers. The textural triangle (see Figure 4.13) should be kept in mind when determining the textural class by the feel method as explained in Box 4.2 and Figure 4.16.

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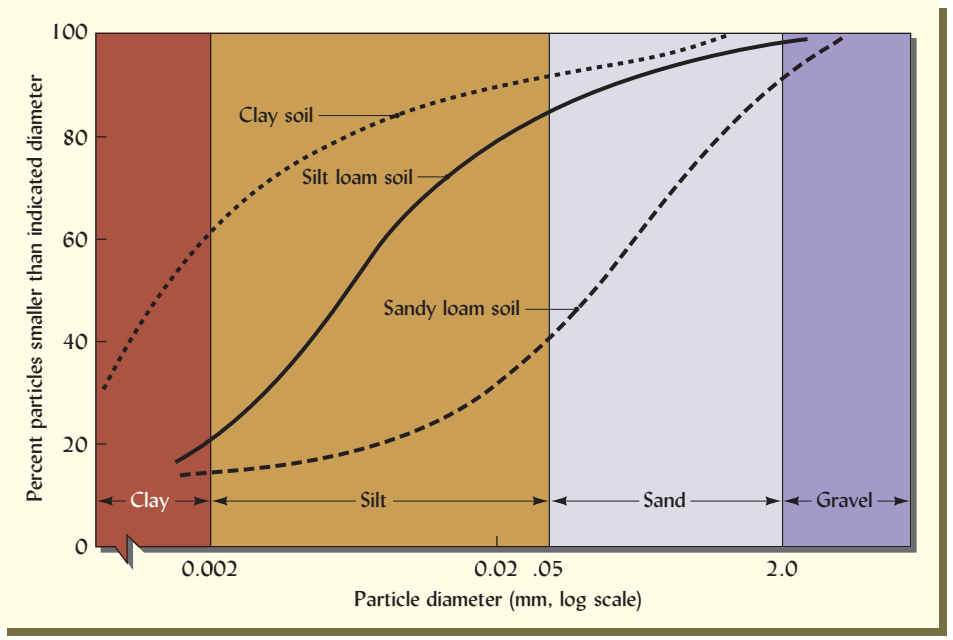

Figure 4.14 *Particle-size distribution in three soils varying widely in their textures. Note that there is a gradual transition in the particle-size distribution in each of these soils.*

It is important to note that soils are assigned to textural classes *solely* on the basis of the mineral particles of sand size and smaller; therefore, the percentages of sand, silt, and clay always add up to 100%. The amounts of stone and gravel are rated separately. Organic matter is not considered. Figure 4.14 presents particle-size distribution curves for soils representative of three textural classes. The fact that these curves are smooth emphasizes that even though discrete particle size classes have been defined (e.g., coarse sand or fine clay), there exists continuum of particle sizes in any soil. The textural triangle in Figure 4.13 also enables us to use laboratory particle-size analysis data to check the accuracy of field textural determinations by feel.

Laboratory Particle-Size Analyses

The first and sometimes most difficult step in a particle-size analysis is the complete dispersion of a soil sample in water, so even the tiniest clumps are broken down into individual, primary particles. Dispersion is usually accomplished using chemical treatments along with a high-speed blender, shaker, or ultrasonic vibrator.

Once suspended in water, most labs use a combination of sieving and sedimentation to determine the distribution of particle sizes in a soil sample. The procedure involves washing the suspended particles through standard sieves with openings sized to separate the coarse fragments and sand separates, permitting the silt and clay fractions to pass through. A sedimentation procedure is then used to determine the amounts of silt and clay (Figure 4.17). The principle involved is simple. Because soil particles are denser than water, they tend to sink, settling at a velocity that is proportional to their size. In other words, "The bigger they are, the faster they fall." The equation that describes this relationship is referred to as *Stokes' law* (Box 4.3).

The classical sedimentation method for particle size analysis just described is quite time-consuming, laborious, requires large soil samples, and is subject to a variety of inaccuracies. As a result, computerized instruments have been developed that use laser light to rapidly determine particle size distribution in small samples of soil dispersed in water (Figure 4.18). Laser diffraction methods are fast and precise, but not necessarily accurate. Compared to sedimentation, lasers accurately determine particle size for samples of tiny spherical glass beads, but they tend to greatly underestimate clay while overestimating silt and sand when applied to oddly shaped soil particles comprised of many different minerals that diffract light differently. These limitations remind us that tremendous complexity and heterogeneity makes it a challenge to measure almost any soil property and keeps soils investigations at the frontier of science.

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BOX 4.2

A METHOD FOR DETERMINING TEXTURE BY FEEL

The first, and most critical, step in the texture-by-feel method is to knead a walnut-sized sample of moist soil into a uniform puttylike consistency, slowly adding water if necessary. This step may take a few minutes, but a premature determination is likely to be in error as hard clumps of clay and silt may feel like sand grains. The soil should be moist, but not quite glistening. Try to do this with only one hand so as to keep your other hand clean for writing in a field notebook (and shaking hands with your client).

While squeezing and kneading the sample, note its malleability, stickiness, and stiffness, all properties associated with the clay content. A high silt content makes a sample feel smooth and silky, with little stickiness or resistance to deformation. A soil with a significant content of sand feels rough and gritty, and makes a grinding noise when rubbed near one's ear.

Get a feel for the amount of clay by attempting to squeeze a ball of properly moistened soil between your thumb and the side of your forefinger, making a ribbon of soil. Squeeze out the ribbon little by little, making it as long as possible until it breaks from its own weight (see Figure 4.15). Interpret your observations as indicated in Figure 4.16.

A more precise estimate of sand content (and hence more accurate placement in the horizontal dimension of the textural class triangle) can be made by wetting a pea-sized clump of soil in the palm of your hand and smearing it around with your finger until your palm becomes coated with a souplike suspension of soil. The sand grains will stand out visibly and their volume as compared to the original "pea" can be estimated, as can their relative size (fine, medium, coarse, etc.).

Figure 4.15 *The "feel" method for determining soil textural class. A moist soil sample is rubbed between the thumb and forefingers and squeezed out to make a "ribbon." (Top) The gritty, noncohesive appearance and short ribbon of a sandy loam containing about 15% clay. (Middle) The smooth, dull appearance and crumbly ribbon characteristic of a silt loam. (Bottom) The smooth, shiny appearance and long, flexible ribbon of a clay.* (Photos courtesy of Ray R. Weil)

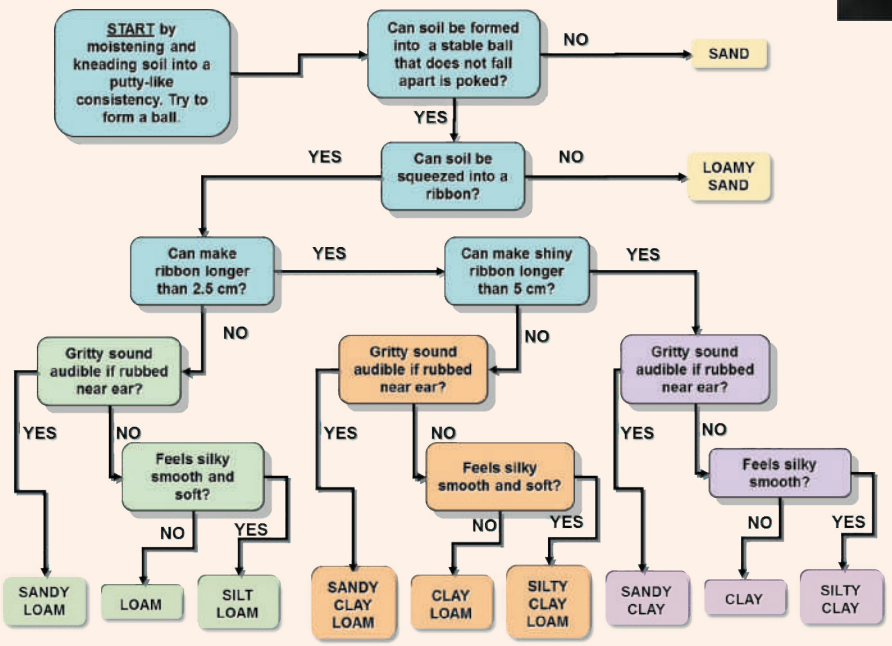

Figure 4.16 *Flow chart for determining textural class by feel. To use the chart, to determine the texture of a soil, begin at the top left corner.* [Diagram Weil (2009)]

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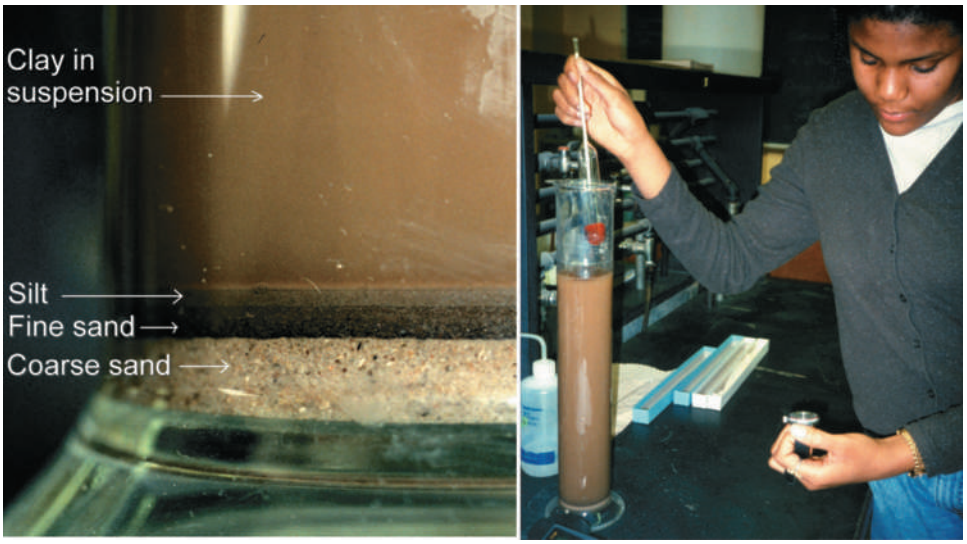

Figure 4.17 *In performing particle-size analysis, a sample of soil (with organic matter removed) is suspended in water, stirred vigorously, and then allowed to settle. A hydrometer (right) can indicate the mass of particles remaining in suspension after different settling times (it floats higher when more soil is in suspension). Stokes' Law is used to calculate the smallest effective diameter of the particles still in suspension at these times. (Left) The layers of sand and silt that have settled out after 7 hours.* (Photos courtesy of Ray R. Weil)

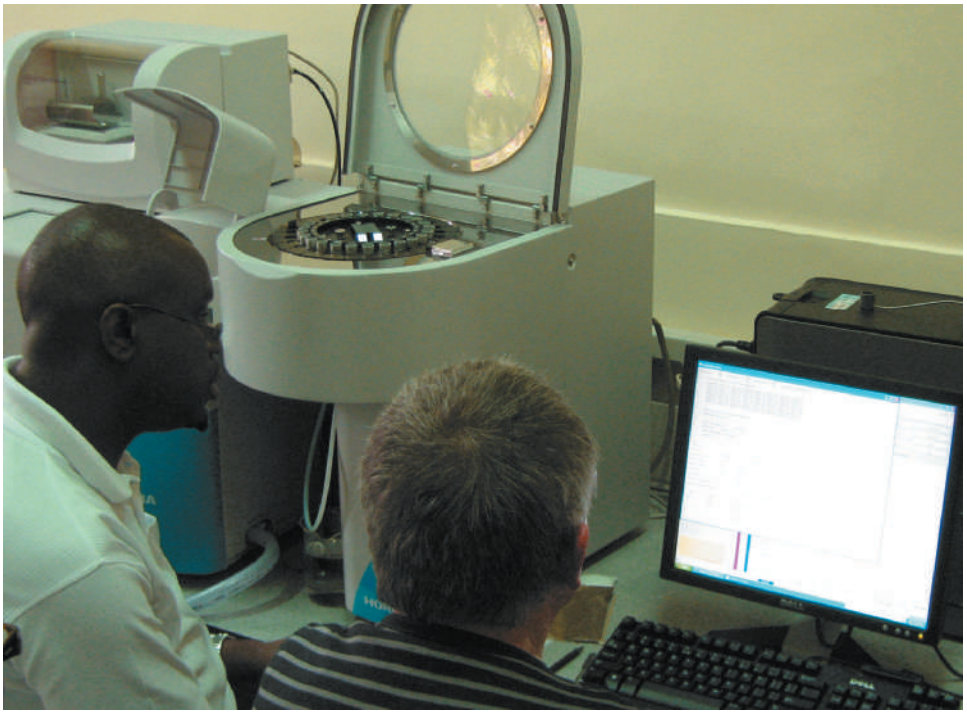

Figure 4.18 *A computerized and semi-automated laser diffraction instrument is used to analyze soil particle size distribution in a lab in Kenya. Laser light is diffracted ("bent") at greater angles by smaller particles. Therefore, when parallel laser light beams pass through a dispersed soil sample suspended in water, the intensity of the diffracted light sensed at different angles from the sample can be interpreted through a set of complex calculations to indicate the number of particles of any particular diameter. For a comparison of strengths and weaknesses of laser and sedimentation methods see Di Stefano et al. (2010)* (Photo courtesy of Ray R. Weil)

BOX 4.3

STOKES' LAW AND PARTICLE SIZE DETERMINED BY SEDIMENTATION

The complete expression of Stokes' law tells us the velocity V of a particle falling through a fluid is directly proportional to the gravitational force g, the difference between the density of the particle and the density of the fluid ($D_s - D_f$) and the square of the effective particle diameter (d^2). The effective diameter is referred to because Stokes' law applies to smooth, round particles. Since most soil particles are neither smooth nor round, sedimentation techniques determine the *effective* diameters, not necessarily the actual diameter of the soil particle. The settling velocity is *inversely* proportional to the viscosity or "thickness" of the fluid η. Since velocity equals distance h divided by time t we can write Stokes' law as:

$$V = \frac{h}{t} = \frac{d^2 g(D_s - D_f)}{18\eta}$$

Where:

g = gravitational force = 9.81 newtons per kilogram (9.81 N/kg)

(continued)

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BOX 4.3

STOKES' LAW AND PARTICLE SIZE DETERMINED BY SEDIMENTATION *(CONTINUED)*

η = viscosity of water at 20°C = 1/1000 newton-seconds per m^2 (10^3 Ns/m^2)

D_s = density of the solid particles, for most soils = 2.65×10^3 kg/m^3

D_f = density of the fluid (i.e., water) = 1.0×10^3 kg/m^3

Substituting these values into the equation, we can write:

$$V = \frac{h}{t}$$

$$= \frac{d^2 \times 9.81\ N/kg \times (2.65 \times 10^3\ kg/m^3 - 1.0 \times 10^3\ kg/m^3)}{18 \times 10^{-3}\ Ns/m^2}$$

$$= \frac{9.81\ N/kg \times 1.65 \times 10^3\ kg/m^3}{18 \times 10^{-3}\ Ns/m^2} \times d^2$$

$$= \frac{16.19 \times 10^3\ N/m^3}{0.018\ Ns/m^2} \times d^2$$

$$= \frac{9 \times 10^5}{sm} \times d^2 = kd^2, \text{ where } \ldots\ k = \frac{9 \times 10^5}{sm}$$

Note that $V = kd^2$ is a highly simplified formula for Stoke's law in which k represents a constant related to the acceleration of gravity and the nature of the liquid.

Let's choose to sample or measure a soil suspension at 0.1 m (10 cm) depth (Figure 4.15). We can calculate the seconds of settling time we must allow if we want the smallest silt particle to have just passed our sampling depth so our sample will contain only clay.

Chosen: $h = 0.1$ m and $d = 2 \cdot 10^{-6}$ m (0.002 mm, smallest silt)

Solving for t we can write:

Therefore:

$$t = \frac{0.1\ m}{(2 \times 10^{-6}\ m)^2 \times 9 \times 10^5\ s^{-1}/m^{-1}} = 27{,}777\ sec$$

$$= 463\ min = 7.72\ hours$$

By comparison, the smallest sand particle ($d = 0.05$ mm) would make the same journey in only 44 seconds.

4.4 STRUCTURE OF MINERAL SOILS[3]

As mentioned in the chapter introduction, a soil can be thought of as a complex building with the texture representing the sizes of building blocks or bricks used in its construction. It is useful to continue this architecture analogy and consider how soil particles (analogous to bricks) are grouped together to create structure (analogous to a house). The arrangement of various sized bricks into a house with associated windows, doors, and hallways represents the formation of soil structure and the associated complex pores and channels (Figure 4.19). The

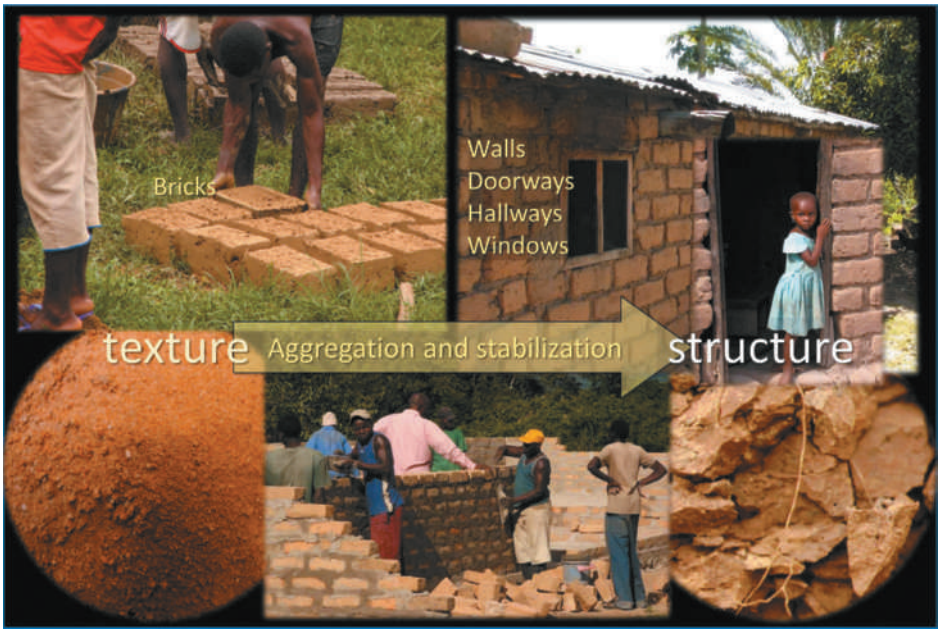

Figure 4.19 *Particles (analogous to bricks) are grouped together to create structure (analogous to a house). The cement and fibers that hold the bricks in place represent the microbial glues, roots, and fungal hyphae that stabilize soil structure and create a complex of windows, hallways, and rooms—"living spaces" for microbes and "storage spaces" for water, gases, nutrients and other chemicals.* (Photos courtesy of Ray R. Weil)

[3]For fascinating insights into the relationships between soil structure and soil biology, see Ritz and Young (2011).

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cement that holds the bricks in place represents the microbial glues, roots, and fungal hyphae that stabilize soil structure. In building a house, the manner in which the building blocks are put together determines the nature of the rooms and passageways.

Soil structure describes the *spatial arrangement* of particles to complex aggregations, pores, and channels. Sand, silt, clay, and organic particles become aggregated together due to various forces and at different scales to form distinct structural units called **peds** or **aggregates** (Figure 4.20). When a mass of soil is excavated and gently broken apart, it tends to break into peds along natural zones of weakness. These zones exhibit low tensile strength because particles within a ped or aggregate are more strongly attracted to one another than to the particles of the surrounding soil. Although *aggregate* and *ped* can be used synonymously, the term *ped* is most commonly used to describe the large-scale structure evident when observing soil profiles and involving structural units which range in size from a few mm to about 1 m. At this scale, the attraction of soil particles to one another in patterns that define structural units is influenced mainly by such physical processes as freeze–thaw, wet–dry, shrink–swell, the penetration and swelling of plant roots, the burrowing of soil animals, and the activities of people and machines. Structural peds should not be confused with **clods**—the compressed, cohesive chunks of soil that can form artificially when wet soil is plowed or excavated.

Most large peds are composed of, and can be broken into, smaller peds or aggregates (Figure 4.20). The networks of **pores** within and between the aggregates constitute a key aspect of soil structure (see Section 4.7). The pore network greatly influences the movement of air and water, the growth of plant roots, and the activities of soil organisms, including the accumulation and breakdown of organic matter. Such practices as timber harvest, grazing, tillage, trafficking, and manuring impact soils largely through their effects on soil pores, especially in the surface horizons.

The biological, chemical, and physical forces involved in the formation, stabilization, and management of soil aggregates of various sizes will be discussed in Sections 4.5 and 4.6. First we will examine the nature and types of structure observable in soil profiles.

Types of Soil Structure[4]

Many types or shapes of peds occur in soils, often within different horizons of a particular soil profile. Some soils may exhibit a **single-grained** structural condition in which particles

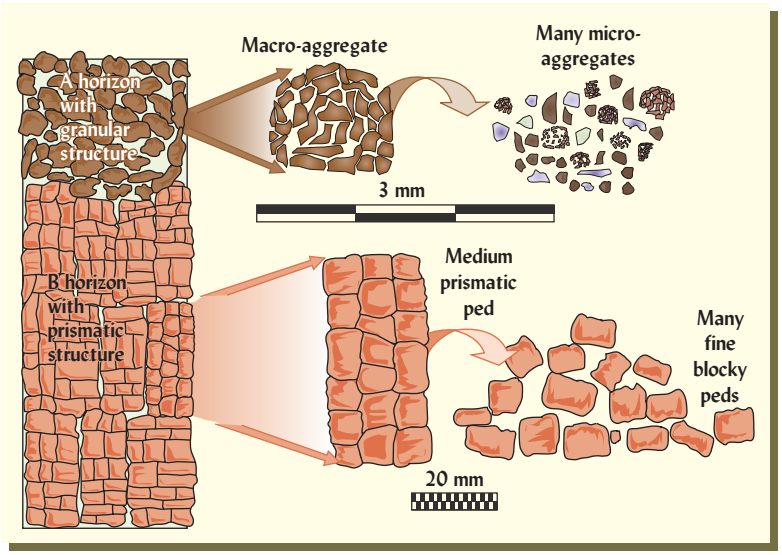

Figure 4.20 *Larger structural units observable in a soil profile each contain many smaller units. The lower example shows how large prismatic peds typical of B horizons break down into smaller peds (and so on). The upper example illustrates how microaggregates smaller than 0.25 mm in diameter are contained within the granular macroaggregates of about 1 mm diameter that typify A horizons. The microaggregates often form around and occlude tiny particles of organic matter originally trapped in the macroaggregate. Note the two different scales for the prismatic and granular structures.* (Diagram courtesy of Ray R. Weil)

[4]In the U.S. *Soil Survey Handbook* (USDA-NRCS, 2005), the single-grained and massive conditions are described as *structureless*.

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are not aggregated. The loose sand in wind-blown dunes or loose dust accumulations such as freshly deposited loess are examples of this single-grain structural condition. At the opposite extreme, some soils (such as certain clay sediments) occur as large, cohesive masses of material and are described as exhibiting a **massive** structural condition. However, most soils exhibit some type of aggregation and are composed of peds that can be characterized by their shape (or *type*), size, and distinctness (or *grade*). The four principal soil ped shapes are *spheroidal*, *platy*, *prismlike*, and *blocklike* (see below and Figure 4.21).

Spheroidal. **Granular** structure consists of roughly spheroidal **aggregates** that may be separated from each other in a loosely packed arrangement (see Figure 4.21*a*). They typically range from <1 to as large as 10 mm in diameter. In reference to this type of structure, the term *aggregate* is used more commonly than *ped*. Granular structure characterizes many surface soils (usually A horizons), particularly those high in organic matter. Consequently, this is the principal type of soil structure affected by management.

Platelike. **Platy** structure, characterized by relatively thin horizontal sheetlike peds (plates), may be found in both surface and subsurface horizons. In most instances, the plates have developed as a result of soil-forming processes. However, unlike other structure types, platy structure may also be inherited from soil parent materials, especially those laid down by water or ice. In some cases compaction of clayey soils by heavy machinery can create platy structure (see Figure 4.21*b*).

Blocklike. **Blocky** peds are irregular, roughly cubelike (Figure 4.22), and range from about 5 to 50 mm across. The individual blocks are not shaped independently, but are molded by the shapes of the surrounding blocks. When the edges of the blocks are sharp and the rectangular faces distinct, the subtype is designated **angular blocky** (see Figure 4.21*c*). When some rounding has occurred, the peds are referred to as **subangular blocky** (see Figure 4.21*d*). These types are usually found in B horizons, where they promote drainage, aeration, and root penetration.

Prismlike. **Columnar** and **prismatic** structures are characterized by vertically oriented prisms or pillarlike peds that vary in size among different soils and may have a diameter of 150 mm or more (Figure 4.23). Columnar structure (see Figure 4.21*e*), which has pillars with distinct, rounded tops, is mainly found in subsoils high in sodium (e.g., natric horizons; see Section 3.2). When the tops of the prisms are relatively angular and flat horizontally, the structure is designated as prismatic (see Figure 4.21*f*). Both prismlike structures are often associated with swelling types of clay. Prismatic structure commonly occurs in subsurface horizons in arid and semiarid regions and, when well developed, provides a very striking feature of the profile (see Figure 10.18). In humid regions, prismatic structure sometimes occurs in poorly drained soils, in human-made soils forming from structureless sediments deposited on land, and in fragipans (see Figures 4.23 and 3.30).

Description of Soil Structure in the Field

In describing soil structure (see Table 19.1), soil scientists note not only the *type* (shape) of the structural peds present, but also the relative *size* (fine, medium, coarse) and degree of development or distinctness of the peds (*grades* such as strong, moderate, or weak). For example, the soil shown in Figure 4.21*d* might be described as having "weak, fine, subangular blocky structure." Generally, the structure of a soil is easier to observe when the soil is relatively dry. When wet, structural peds may swell and press closer together, making the individual peds less well defined. We will now turn our attention to the formation and stabilization of soil structure, particularly the granular aggregates that characterize surface horizons.

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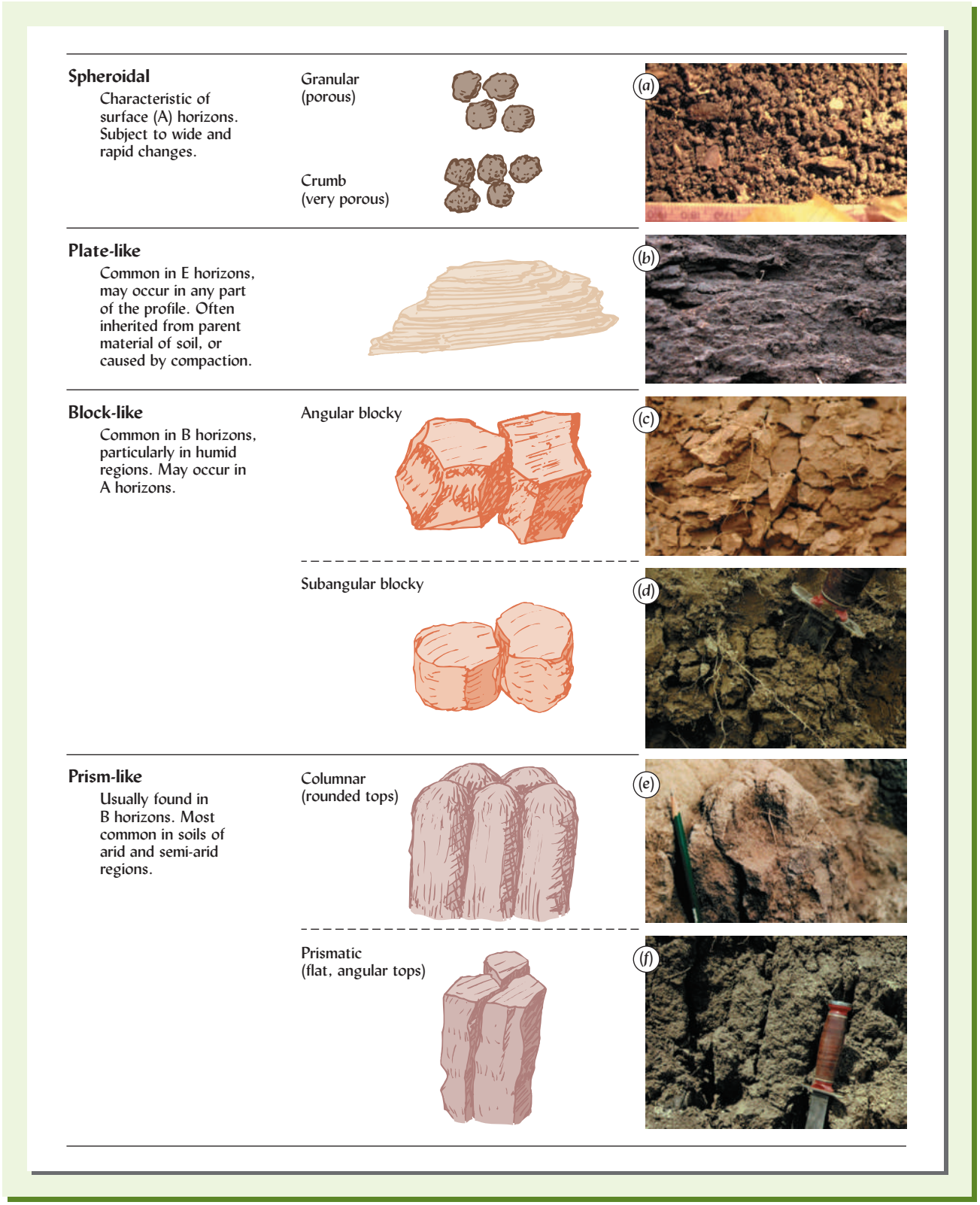

Figure 4.21 *The various structure types (shapes) found in mineral soils. Their typical location is suggested. The drawings illustrate their essential features and the photos indicate how they look in situ. For scale, note the 15-cm-long pencil in (e) and the 3-cm-wide knife blade in (d) and (f).* [Photo (e) courtesy of James L. Arndt/Merjent, Inc.; others courtesy of Ray R. Weil]

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Figure 4.22 *Strong, medium angular blocky peds in the B horizon of an alfisol (Ustalf) in a semiarid region. The knifepoint is prying loose an individual blocky ped. Note the lighter colored surface coatings of illuvial clay that help define and bind the ped together.* (Photo courtesy of Ray R. Weil)

Figure 4.23 *An example of a very large pillar-like ped in the Bw horizon of a seven year old soil. The soil is forming in silty clay material dredged from the bottom of the Potomac River and deposited on land by human activity to create new agricultural soil. This would be described as strong, very coarse, prismatic structure. (Some readers may be interested to learn that Professor Delvin Fanning, who is pointing to the prism in this photo, said he took his first soil science course in 1952 with* The Nature and Properties of Soils *(then in its 5th edition) as the textbook and Nyle C. Brady as the professor.)* (Photo courtesy of Ray R. Weil)

4.5 FORMATION AND STABILIZATION OF SOIL AGGREGATES

The granular aggregation of surface soils is a highly dynamic soil property. Some aggregates disintegrate and others form anew as soil conditions change. Generally, smaller aggregates are more stable than larger ones, so maintaining the much-prized larger aggregates requires great care. We will discuss practical means of managing soil structure after we consider the factors responsible for aggregate formation and stabilization.

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Hierarchical Organization of Soil Aggregates[5]

Surface horizons are usually characterized by roundish granular structure that exhibits a hierarchy in which relatively large **macroaggregates** (0.25–5 mm in diameter) are comprised of smaller **microaggregates** (2–250 µm). The latter, in turn, are composed of tiny packets of clay and organic matter only a few µm in diameter. You may easily demonstrate the existence of this *hierarchy of aggregation* by selecting a few of the largest aggregates in a soil and gently crushing or picking them apart to separate them into many smaller-sized pieces. Then try rubbing the tiniest of these soil crumbs between your thumb and forefinger. You will find that even the smallest specks of soil usually break down into a smear of still smaller particles of silt, clay, and humus (Figure 4.25). The hierarchical organization of aggregates seems to be characteristic of most soils, with the exception of certain Oxisols and some very young Entisols. Small particles of organic matter are often occluded inside the macro- and microaggregates. At each level in the hierarchy of aggregates, different factors are responsible for binding together the subunits (Figure 4.24).

Factors Influencing Aggregate Formation and Stability in Soils

Both biological and physical–chemical processes are involved in the formation of soil aggregates. Physical–chemical processes tend to be the most important at the smaller end of the scale, biological processes at the larger end. The physical–chemical processes of aggregate formation are associated mainly with clays and, hence, tend to be of greater importance in finer-textured soils. In sandy soils that have little clay, aggregation is almost entirely dependent on biological processes.

Physical–Chemical Processes

Most important among the physical–chemical processes are: (1) flocculation, the mutual attraction among clay and organic molecules; and (2) the swelling and shrinking of clay masses.

Flocculation of Clays and the Role of Adsorbed Cations. Except in very sandy soils that are almost devoid of clay, aggregation begins with the **flocculation** of clay particles into microscopic clumps or *floccules* (Figure 4.26). If two clay platelets come close enough to each other, cations compressed in a layer between them will attract the negative charges on both platelets, thus serving as bridges to hold the platelets together. These processes lead to the formation of a small "stack" of parallel clay platelets, termed a *clay domain*. Other types of clay domains

Figure 4.24 *Even the tiniest visible "particles" of soil usually turn out—if rubbed—to be aggregates consisting of thousands of primary soil particles.* (Photos courtesy of Ray R. Weil)

[5]The hierarchical organization of soil aggregates was first put forward by Tisdall and Oades (1982). For a review of advances in this area, see Six et al. (2004).

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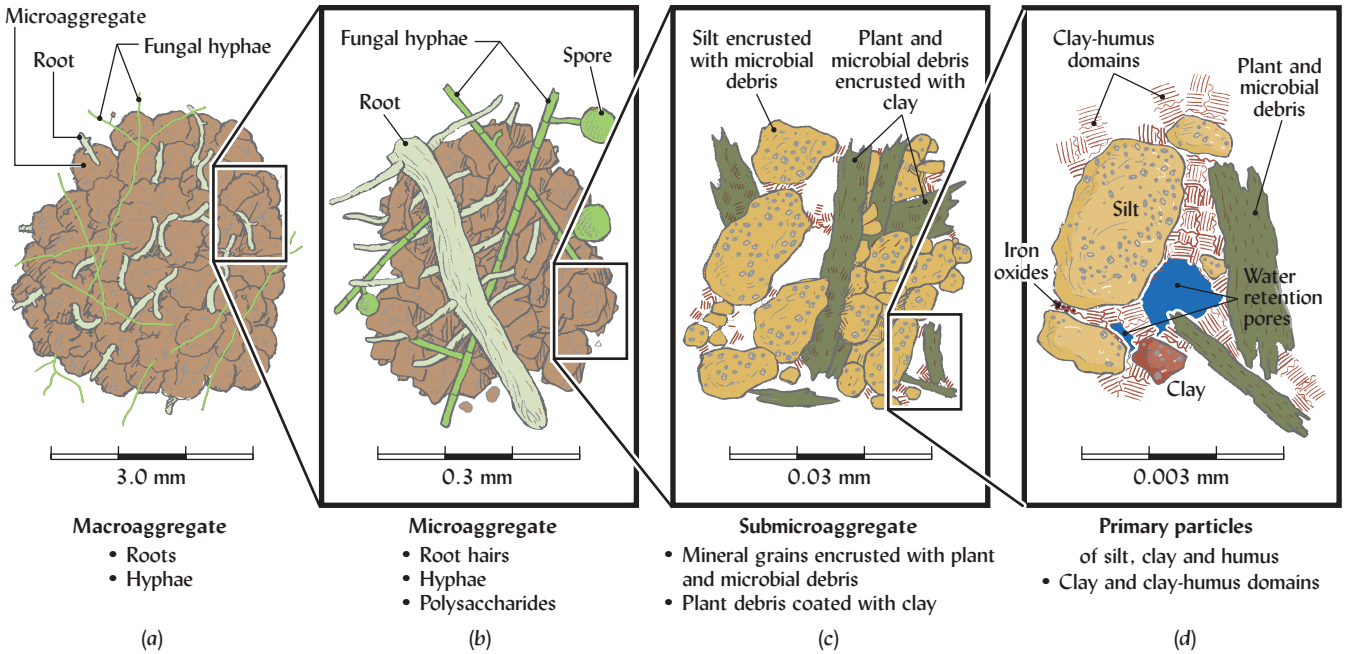

Figure 4.25 *Larger aggregates are often composed of an agglomeration of smaller aggregates. This illustration shows four levels in this hierarchy of soil aggregates. The different factors important for aggregation at each level are indicated. (a) A* macroaggregate *composed of many microaggregates bound together mainly by a kind of sticky network formed from fungal hyphae and fine roots. (b) A* microaggregate *consisting mainly of fine sand grains and smaller clumps of silt grains, clay, and organic debris bound together by root hairs, fungal hyphae, and microbial gums. (c) A very small submicroaggregate consisting of fine silt particles encrusted with organic debris and tiny bits of plant and microbial debris (called* particulate organic matter*) encrusted with even smaller packets of clay, humus, and Fe or Al oxides. (d) Clusters of parallel and random clay platelets interacting with Fe or Al oxides and organic polymers at the smallest scale. These organoclay clusters or* domains *bind to the surfaces of humus particles and the smallest of mineral grains.* (Diagram courtesy of Ray R. Weil)

are more random in orientation, resembling a house of cards. These form when the positive charges on the edges of the clay platelets attract the negative charges on the planar surfaces (Figure 4.27). Multivalent cations (especially Ca^{2+}, Fe^{2+}, and Al^{3+}) also complex with hydrophobic organic molecules, allowing them to bind to clay surfaces.

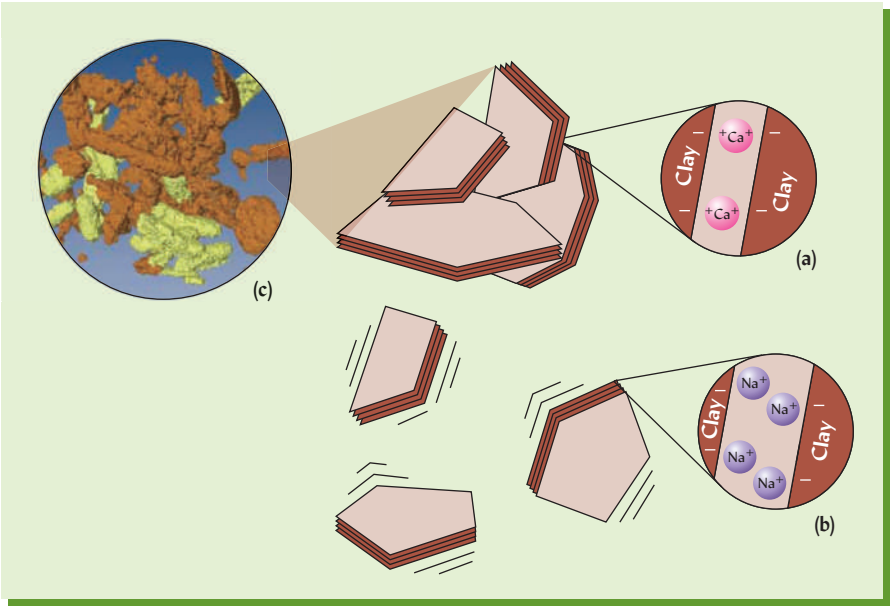

Figure 4.26 *The role of cations and bacteria in clay flocculation.* (a) *Di- and trivalent cations like Ca^{2+}, Fe^{3+}, and Al^{3+} are tightly adsorbed, form bridges that bring clay particles together, and effectively neutralize negative charges on clay surfaces.* (b) *Monovalent ions, especially N^{a+}, with a relatively large hydrated radius and low charge can cause clay particles to repel each other and create a dispersed condition because (1) the large hydrated N^{a+} ions cannot get close enough to effectively neutralize the negative charges, (2) the single charge on N^{a+} is not effective in forming a bridge between clay particles, and (3) compared to di- or trivalent ions, two or three times as many monovalent ions must crowd between clay particles in order to neutralize the charges on the clay surfaces.* (c) *due to charges on their cells walls and sticky exocellular compounds, bacteria (yellow) further flocculate clay particles (brown).* (Diagrams (a) and (b) courtesy of Ray R. Weil; *X-ray tomographic image* (c) from Thieme et al. (2003))

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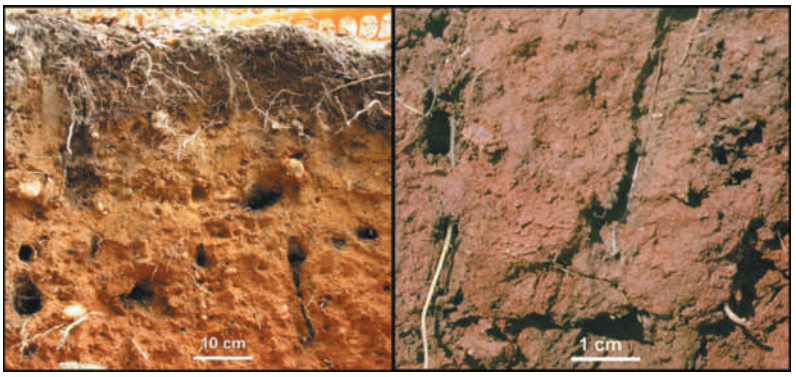

Figure 4.27 *Biopores formed by soil organisms.* (Left) *Upper horizons in a forested Ultisol in Maryland, USA, are shot through with old tree root channels in which the original tree roots have long ago decayed. The channels are lined with dark organic matter and serve as "superhighways" for current root growth.* (Right) *Earthworm burrows in the Bt horizon (60 cm depth) of an Inceptisol in Pennsylvania, USA, managed with cover crops and no-till techniques. Nutrient rich organic materials line the burrows, which serve provide easy access to subsoil water for these sweetpepper roots.* [Photos courtesy of Ray R. Weil]

Clay/humus domains form bridges that bind to each other and to fine silt particles (mainly quartz), creating the smallest size groupings in the hierarchy of soil aggregates (Figure 4.23*d*). These domains, aided by the flocculating influence of certain polyvalent cations (again, mainly Ca^{2+}, Fe^{2+}, and Al^{3+}) and humus, provide much of the long-term stability for the smaller (<0.25 mm) microaggregates. In some highly weathered clayey soils (Ultisols and Oxisols) the cementing action of iron oxides and other inorganic compounds produces very stable small aggregates called **pseudosand**.

When certain cations (especially Na^+, but to a lesser degree K^+ and even Mg^{2+}) with less flocculating ability than Ca^{2+} or Al^{3+} are prominent, the attractive forces are not able to overcome the natural repulsion of one negatively charged clay platelet by another (Figure 4.26). The clay platelets cannot approach closely enough to flocculate, so remain dispersed and cause the soil to become gellike, impervious to water and air, and very undesirable from the standpoint of plant growth. This dispersed condition is most dramatically stimulated by Na^+ ions and is most common in soils of arid and semiarid areas (more details in Section 10.6).

Volume Changes in Clayey Materials. As a soil dries out and water is withdrawn, the platelets in clay domains move closer together, causing the domains and, hence, the soil mass to shrink in volume. As a soil mass shrinks, cracks will open up along zones of weakness. Over the course of many cycles (as occur between rain or irrigation events in the field) the network of cracks becomes better defined. In one of many ways in which physical and biological soil processes interact, plant water uptake dries the root zone and accentuates the physical aggregation processes associated with wetting and drying.

Freezing and thawing cycles have a similar effect, since the formation of ice crystals is a drying process that also draws water out of clay domains. The swelling and shrinking actions that accompany freeze–thaw and wet–dry cycles in soils create fissures and pressures that alternately break apart large soil masses and compress soil particles into defined structural peds. The aggregating effects of these water and temperature cycles are most pronounced in soils with a high content of swelling-type clays (see Chapter 8), especially Vertisols, Mollisols, and some Alfisols (see Chapter 3).

Biological Processes

Activities of Soil Organisms. Among the biological processes of aggregation, the most prominent are: (1) the burrowing and molding activities of soil animals, (2) the enmeshment of particles by sticky networks of roots and fungal hyphae, and (3) the production of organic glues by microorganisms, especially bacteria and fungi. Earthworms (and termites) move soil particles about, often ingesting them and forming them into pellets or casts (see Chapter 11). In some forested soils, the surface horizon consists primarily of aggregates formed as earthworm castings (see, e.g., Figure 4.21*a*). Plant roots also move particles about as they push their way through the soil. This movement forces soil particles to come into close contact with

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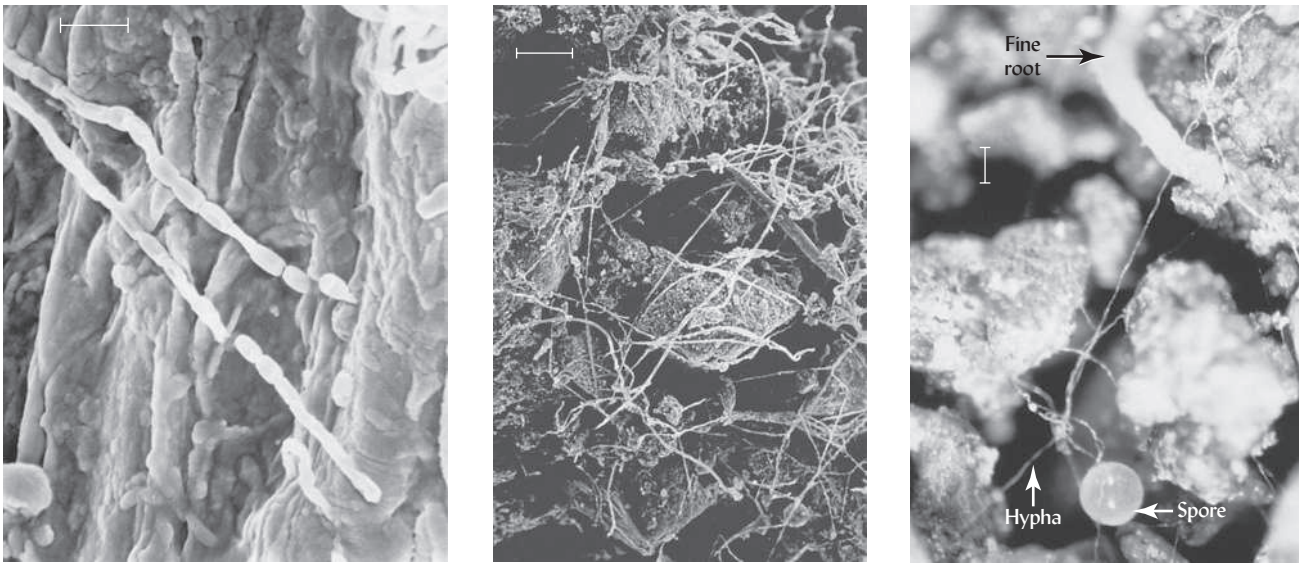

(*a*) (*b*) (*c*)

Figure 4.28 *Fungal hyphae binding soil particles into aggregates. (a) Close-up of a hyphae growing over the surface of a mineral grain encrusted with microbial cells and debris. Bar = 10 μm. (b) An advanced stage of aggregation during the formation of soil from dune sands. Note the net of fungal hyphae and the encrustation of the mineral grains with organic debris. Bar = 50 μm. (c) Hyphae of the root-associated fungus from the genus* Gigaspora *interconnecting particles in a sandy loam from Oregon, USA. Note also the fungal spore and the plant root. Bar = 320 μm.* [Photos (*a*) and (*b*) courtesy of Sharon L. Rose, Willamette University; photo (*c*) courtesy of R. P. Schreiner, USDA-ARS, Corvallis, OR]

each other, encouraging aggregation. At the same time, the channels created by plant roots and soil animals serve as large conduits for new root growth. The channels also break up clods and help to define larger soil structural units (see Figure 4.27).

Plant roots (particularly root hairs) and fungal hyphae exude sugarlike polysaccharides and other organic compounds, forming sticky networks that bind together individual soil particles and tiny microaggregates into larger macroaggregates (see Figures 4.25*a* and 4.28). The threadlike fungi that associate with plant roots (called *mycorrhizae*; see Section 11.9) produce a sticky sugar–protein called **glomalin**, which is thought to be an effective cementing agent (Box 4.4).

As they decompose plant residues, bacteria also produce organic glues such as the polysaccharides shown in Figure 4.31 intermixed at a very small scale with clay. Many of these root and microbial organic glues resist dissolution by water and so not only enhance the formation of soil aggregates but also help ensure their stability over a period of months to a few years. These processes are most notable in surface soils, where root and animal activities and organic matter accumulation are greatest.

Influence of Organic Matter. In most temperate zone soils, the formation and stabilization of granular aggregates is primarily influenced by soil organic matter (see Figure 4.31). Organic matter provides the energy substrate that makes possible the previously mentioned biological activities. During the aggregation process, soil mineral particles (silts and fine sands) become coated and encrusted with bits of decomposed plant residue and other organic materials. Organic polymers resulting from decay chemically interact with particles of silicate clays and iron and aluminum oxides. These compounds help orient the clays into packets (domains), which form bridges between individual soil particles, thereby binding them together in water-stable aggregates (see Figure 4.16*d*). In Figure 4.32 we can directly observe bacterial polymers and organomineral domains that bind soil particles.

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BOX 4.4

GLOMALIN AND AGGREGATES TAKE SYMBIOSIS TO ANOTHER LEVEL[a]

Scientists continue to discover new ways in which soil microorganisms help create and stabilize soil aggregates. Certain **mycorrhizal** fungi (see Section 11.9) live in a symbiotic state with the roots of many wild and agricultural plants. The plants provide the fungi with sugars and the fungi help plants obtain nutrients from the soil. Scientists have discovered a mixture of glycoproteins (sugar–proteins), called glomalin that is produced by the **hyphae** (thin strands) of these fungi. Although the function of glomalin in the fungus is still under investigation, substantial amounts of glomalin-related proteins have been identified in soils. Current thinking suggests that these iron-binding glycoproteins are quite resistant to decay and therefore accumulate to relatively high levels in soils.

Several types of observations point to a role for glomalin in soil aggregate stabilization. (1) The glomalin-related proteins are usually found in higher concentration in stable than in unstable aggregates in soils of both temperate and tropical regions. (2) Using immunofluorescence antibody techniques, soil scientists can detect glomalin-related proteins on the surfaces of soil aggregates (Figure 4.29). (3) Fungi may produce glomalin partly to increase soil aggregation and create larger pores for better growth of their hyphae (Figure 4.30). Carrot roots and mycorrhizal fungi were grown in containers with barriers that allowed fungi but not roots to grow into chambers filled with large (~1 mm) or small (~0.1 mm) diameter glass beads (to simulate unaggregated and aggregated soil, respectively). Although root growth and infection by mycorrhizal fungi were about the same for each bead size, the hyphae grew only 1/6 as much in the small as in the large beads, suggesting that lack of large pores can restrict fungal growth in soils. However, the hyphae that did grow in the small beads produced seven times as much total glomalin and 44 times as much glomalin per unit of hyphal length as was produced in the large beads.

So it seems that plant investment of photosynthates (sugar) into the relationship with fungi may indirectly help stimulate a better aggregated soil that is more suitable for the survival and growth of *both* plants *and* fungi. Land managers may be able to take advantage of this knowledge by using practices, such as reducing tillage and applying mulches, which favor the fungi that stimulate soil aggregation.

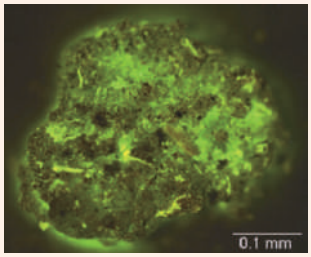

Figure 4.29 *Soil aggregate with fluorescing green areas indicating presence of glomalin by its reaction with a specific antibody.* (Image courtesy of Kris Nichols, USDA-ARS, Mandan, ND)

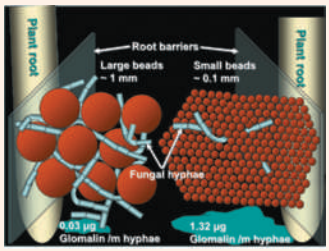

Figure 4.30 *Experiment suggesting fungi produce glomalin partly to aggregate soil and create large pores for better growth of their hyphae.* [Diagram courtesy of Ray R. Weil, from data in Rillig and Steinberg (2002)]

[a]For correlations between glomalin proteins and soil aggregation, see Caesar-TonThat et al. (2011); for an update on the nature of the glomalin-related proteins, see Singh (2012).

Influence of Tillage. Tillage can both promote and destroy aggregation. If the soil is not too wet or too dry, tillage can break large clods into natural aggregates, creating a temporarily loose, porous condition conducive to the easy growth of young roots and the emergence of tender seedlings (see Box 4.5). Tillage can also incorporate organic amendments into the soil and kill weeds.

Over longer periods, however, tillage greatly hastens the oxidative loss of soil organic matter, thus weakening soil aggregates. Tillage operations, especially if carried out when the soil is wet, also tend to crush or smear soil aggregates, resulting in loss of macroporosity and the creation of a *puddled* condition.

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Figure 4.31 *The influence of organic matter (OM) on the stability of soil aggregates against slaking (falling apart) when wetted. The two soil samples were collected from adjacent plots on a Beltsville silt loam (Fragiudults), the lower OM soil grew conventionally tilled maize grain crops every year for 20 years. The higher OM soil grew bluegrass sod during the same period, resulting in about 9 g/1000 g (0.9%) more OM in the soil. Although both soils appeared well aggregated when dry (left), when the same amount of water was added to each the aggregates in the low OM soil rapidly fell apart while those in the higher OM soil remained intact. For data associated with these plots, see Weil and Magdoff (2004).* (Photos courtesy of Ray R. Weil)

Influence of Iron/Aluminum Oxides. Many of the highly weathered soils of the tropics (especially Oxisols) have large amounts of iron and aluminum sesquioxides (in largely amorphous forms) that coat soil particles and cement soil aggregates, thereby preventing their ready breakdown when the soil is tilled or wetted. Compared to soils of more temperate regions with similar amounts of organic matter, such tropical soils tend to have much greater aggregate stability, and their aggregation is less dependent on soil organic matter (Figure 4.35).

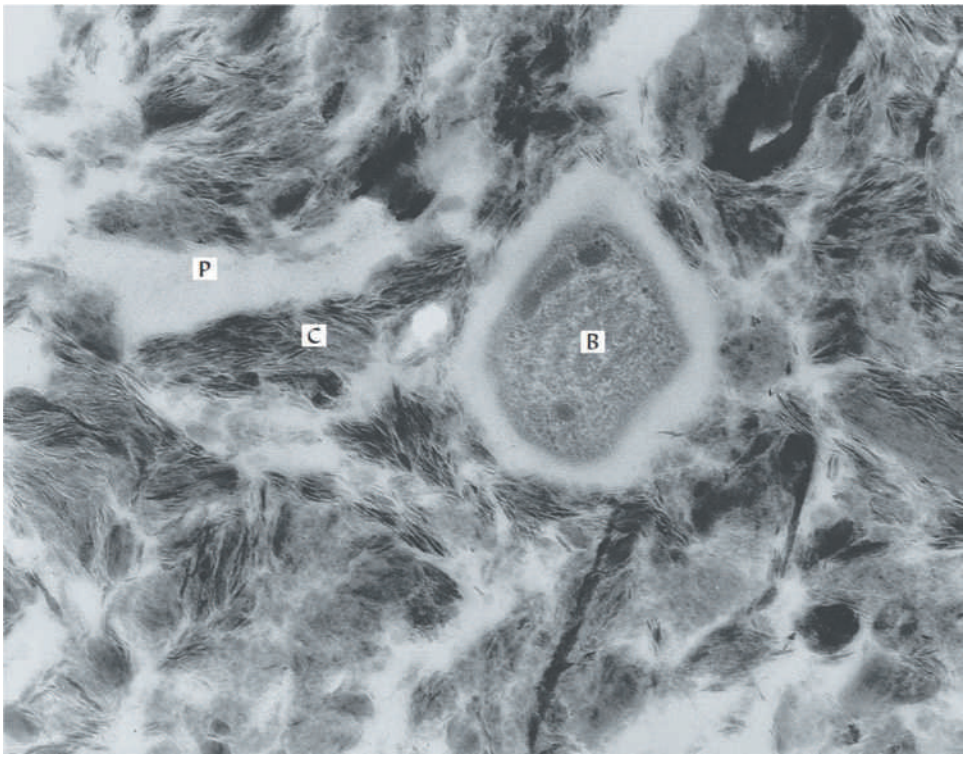

Figure 4.32 *A transmission electron micrograph illustrating the interaction among organic materials and silicate clays in a water-stable aggregate. the dark-colored materials (C) are groups of clay particles that are interacting with organic polysaccharides (P). A bacterial cell (B) is also surrounded by polysaccharides. Note the generally parallel orientation of the clay particles, an orientation characteristic of clay domains.* [From Emerson et al. (1986); Photograph provided by R. C. Foster, Csiro, Glen Osmond, Australia]

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BOX 4.5

PREPARING A GOOD SEEDBED

Early in the growing season, one of the main activities of a farmer or gardener is the preparation of a good seedbed to ensure that the sowing operation goes smoothly, that the seeds germinate quickly, and that the plants come up well spaced.

A good seedbed should be packed firmly enough to ensure the seed can easily imbibe water to begin the germination process. The seedbed soil should also be loose enough to allow easy root elongation and seedling emergence. The seedbed should also be relatively free of large clods between which small seeds could fall and become lodged without sufficient soil contact for germination and too deeply for proper emergence.

Tillage is commonly used to loosen compacted soil, help control weeds, and, in cool climates, help the soil dry out so it will warm more rapidly. On the other hand, the objectives of seedbed preparation may be achieved with little or no tillage if soil and climatic conditions are favorable and a mulch, herbicide, or cover crop is used to control early weeds (Figure 4.33).

Mechanical planters can assist in maintaining a good seedbed, even if no tillage is used. No-till planters are equipped with coulters (sharp steel disks) designed to cut a path through plant residues on the soil surface. No-till planters usually follow the coulter with a pair of sharp cutting wheels called a *double disk opener* that opens a groove in the soil into which the seeds can be dropped (Figure 4.34). Most planters also have a press wheel that follows behind the seed dropper and packs the loosened soil just enough to ensure that the groove is closed and the seed is pressed into contact with moist soil.

Ideally, only a narrow strip in the seed row is packed down to create a seed germination zone, while the soil between the crop rows is left as loose as possible to provide a good rooting zone. The surface of the interrow rooting zone may be left in a rough condition to encourage water infiltration and discourage erosion. The above principles also apply to the home gardener who may be sowing seeds by hand. Instead of a press wheel, the gardener can ensure good seed–soil contact by pressing a board over the seed row or even walking carefully over the seeds, while avoiding compaction in the interrow areas.

Figure 4.33 *Cotton seedlings emerging in three types of seedbed in a Texas Mollisol (Argiustolls).* (Left) *A conventionally tilled seedbed, prepared by stalk shredding, disking, bedding, cultivation to incorporate herbicide, rod weeding before planting (and further weed control cultivation later on).* (Middle) *A no-till seedbed in which seeds were mechanically inserted into soil beneath dead residues of the previous cotton crop (Note white cotton tufts). Herbicides were sprayed to control weeds without soil disturbance.* (Right) *A no-till seedbed protected by a cover crop, which was killed by herbicides shortly before the new crop was planted.* (Photos courtesy of Paul DeLaune, Texas A and M University)

Figure 4.34 *A large no-till planter* (left) *sowing corn seed from yellow hoppers into a field covered by cover crop residues. Very little soil is exposed by the process.* (Right) *A close-up of another notill planter showing how it works to sow seeds with little of the "O horizon" covering of residues from the previous crop. The coulters cut a narrow "V"-shaped slot into the soil and the press wheels closed the slot after the seed is inserted. The complex planter rig also can apply fertilizer and chemicals at the same time that it sows seeds. The fertilizer delivery tube is visible (blue arrow), but the seed is dropped into the soil slot from a tube (yellow arrow, hidden behind the frame) that extends between a pair of coulters called a "double disk opener.* [Photos courtesy of Lynn Betts/Publication Services, LLC (left) and Ray R. Weil (right)]

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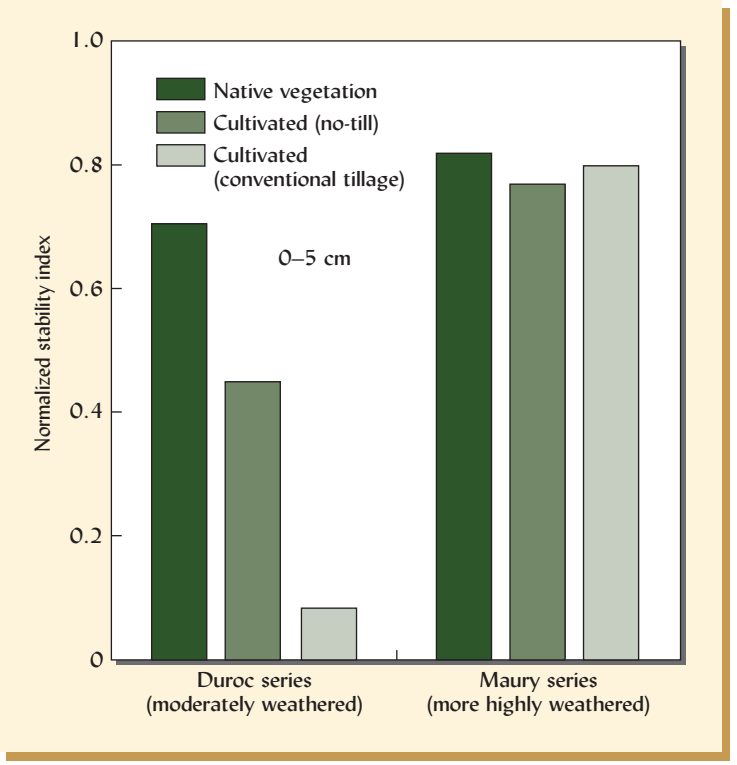

Figure 4.35 *The interaction of soil organic matter with the clay fraction accounts for most of the aggregate stability of such moderately weathered soils as the Duroc series. Consequently, the stability of soil aggregates declines when cultivation, especially with conventional tillage, decreases soil organic matter levels. In more highly weathered soils such as the Maury series, aggregate stability is less dependent on organic matter levels than on the interaction of iron oxide compounds with silicate clays such as kaolinite. The tillage system used therefore has less effect on aggregate stability in these more highly weathered soils. This Figure suggests that cultivated soils of the highly weathered tropics may have greater aggregate stability than their counterparts in temperate zones.* [Redrawn from Six et al. (2000)]

4.6 TILLAGE AND STRUCTURAL MANAGEMENT OF SOILS

When protected under dense vegetation and undisturbed by trampling or tillage, most soils (except perhaps some sparsely vegetated soils in arid regions) possess a surface structure sufficiently stable to allow rapid infiltration of water and to prevent crusting. However, for the manager of cultivated soils, the development and maintenance of stable surface soil structure is a major challenge. Many studies have shown that aggregation and associated desirable soil properties such as water infiltration rate decline under long periods of tilled row-crop cultivation.

Tillage and Soil Tilth

Tilth refers to the physical condition of the soil in relation to plant growth. Tilth is a highly dynamic soil property that depends not only on aggregate formation and stability, but also on such factors as bulk density (see Section 4.7), soil moisture content, degree of aeration, rate of water infiltration, drainage, and capillary water capacity.-

A major aspect of tilth is soil **friability** (see also Section 4.9). Soils are said to be **friable** if their clods are not sticky or hard, but rather crumble easily, revealing their constituent aggregates. Generally, **soil friability** is enhanced when the **tensile strength** (i.e., the force required to pull apart) of individual aggregates is relatively high compared to the tensile strength of the clods. This condition allows tillage or excavation forces to easily break down the large clods, while the resulting aggregates remain stable. As might be expected, friability changes markedly with changes in soil water content, especially for fine-textured soils. Each soil typically has an optimal water content for greatest friability (Figure 4.36).

Clayey soils are especially prone to puddling and compaction because of their high plasticity and cohesion. When puddled clayey soils dry, they usually become dense and hard. Proper timing of trafficking is more difficult for clayey than for sandy soils, because the former take much longer to dry to a suitable moisture content and may also become too dry to work easily. Increased soil organic matter content usually enhances soil friability and

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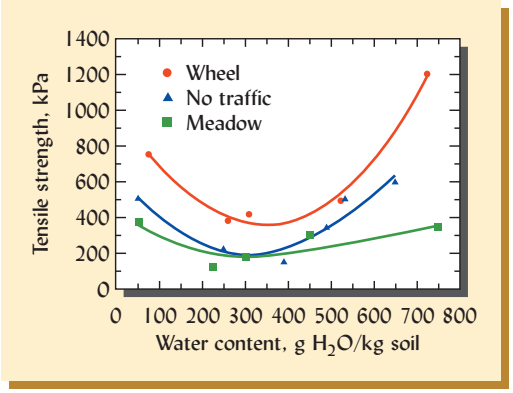

Figure 4.36 *Influence of tillage and wheel traffic on soil strength at various water contents. Tensile strength is the force (measured in kilopascals, kPa) required to break apart soil clods. The lower this force, the easier it is to crumble the soil and the greater the soil friability and workability. The upper two curves represent soil from the wheel tracks (•) and the nontrafficked portion (▲) of a cultivated calcareous clay soil in England. The lowest curve represents the same soil in an adjacent long-term uncultivated meadow (■). There appears to be an optimum water content at which a soil has the lowest tensile strength and is therefore most friable (near 300 g/kg for this soil). Also, the less traffic and tillage, the more friable the soil (the lower the tensile strength), especially when very dry or very wet.* [Drawn from data in Watts and Dexter (1997)]

can partially alleviate the susceptibility of a clay soil to structural damage during tillage and traffic (Figure 4.37).

Some clayey soils of humid tropical regions are much more easily managed than those just described. The clay fraction of these soils is dominated by hydrous oxides of iron and aluminum, which are not as sticky, plastic, and difficult to work. These soils may have very favorable physical properties, since they hold large amounts of water but have such stable aggregates that they respond to tillage after rainfall much like sandy soils.

Farmers in temperate regions typically find their soils too wet for tillage just prior to planting time (early spring), while farmers in tropical regions may face the opposite problem of soils too dry for easy tillage just prior to planting (end of dry season). In tropical and subtropical regions with a long dry season, soil often must be tilled in a very dry state in order to prepare the land for planting with the onset of the first rains. Tillage under such dry conditions can be very difficult and can result in hard clods if the soils contain much sticky-type silicate clay.

In contrast to the situations just discussed, rice farmers often purposely till extensively when their soils are saturated with water (Figure 4.38). They do this to destroy aggregation and greatly reduce water permeability, thus making their soils more suited for holding water in paddies where rice is grown under flooded conditions.

Conventional Tillage and Crop Production

Since the middle ages, the moldboard plow has been the primary tillage implement most used in the western world.[6] Its purpose is to lift, twist, and invert the soil while incorporating crop

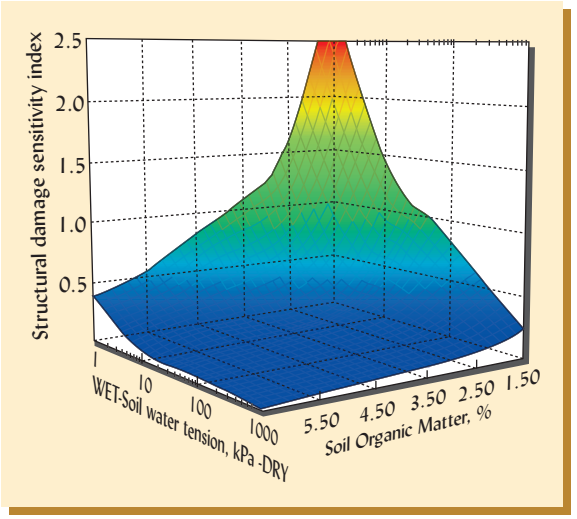

Figure 4.37 *Sensitivity of fine-textured soils to mechanical damage by tillage is increased by wetness and decreased by soil organic matter. The sensitivity index on the vertical axis is based mainly on the tendency for clay dispersion that is associated with soil smearing and aggregate destruction. The soil is especially susceptible to this damage when excessively wet (wetter than the condition termed field capacity, as defined in Section 5.8). It is also evident that a high level of soil organic matter helps protect the aggregated clay during tillage. The relationships shown apply to clayey soils and would be much less extreme in sandy soils.* [Graph based on data in Watts and Dexter (1997)]

[6]For an early but still valuable critique of the moldboard plow, see Faulkner (1943).

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Figure 4.38 *A farmer purposely puddles the soil to prepare his rice paddy for flooding and planting in northern Tanzania. The tillage will destroy the soil structure and reduce soil permeability – results that would normally be avoided on upland agricultural fields, but that are desirable where rice is to be grown on inundated paddies.* (Photo courtesy of Ray R. Weil)

residues and animal wastes into a 10- to 20-cm-thick *plow layer* of soil (Figure 4.39, *left*). The moldboard plow is often supplemented by the disk harrow, which has rolling steel disks that cut up and partially incorporate residues while partially inverting a thinner (5–10 cm thick) layer of soil. Other implements use steel tines to fracture and stir the soil to various depths, but with less complete burial of plant residues. In conventional practice, such primary tillage is followed by a number of secondary tillage operations, such as harrowing to kill weeds and to break up clods, thereby preparing a suitable seedbed. After the crop is planted, the soil may receive further secondary tillage to control weeds. While these tillage operations temporarily loosen the soil, break up clods, and suppress weeds, they also have serious detrimental effects: (1) tillage speeds the loss of soil organic matter and thereby the weakening of soil structure, and (2) most kinds of tillage leave the soil naked without a natural blanket of plant litter to protect the soil surface from sun, rain, and wind.

Conservation Tillage and Soil Tilth

In recent decades, agricultural land-management systems have been developed that minimize the need for soil tillage and leave the soil surface largely covered by plant residues, thereby maintaining soil biological habitat, stabilizing soil structure, conserving soil organic matter, and physically protecting the soil from drying sun, scouring wind, and beating rain (see Section 17.6 for a detailed discussion). For these reasons, the tillage practices followed in these systems are called *conservation tillage*. The U.S. Department of Agriculture defines *conservation tillage* as that which leaves at least 30% of the soil surface covered by residues. Figure 4.39 (*right*) illustrates a no-till operation, where one crop is planted in the residue of another, with virtually no tillage. Other minimum-tillage systems such as chisel plowing permit some stirring of the soil, but still leave a high proportion of the plant residues as a protective cover on the soil surface.

Soil Crusting

Falling drops of water during heavy rain or sprinkler irrigation can beat apart aggregates exposed at the soil surface. In some soils the dilution of salts by this water stimulates the dispersion of clays (Section 10.6). Once the aggregates become dispersed, small particles and dispersed clay tend to wash into and clog the soil pores. The remaining coarse particles at the soil surface become densely packed with little pore space under the influence of beating raindrops. Soon the soil surface is covered with a thin, partially cemented, low permeability layer material called a **surface seal**. The surface seal inhibits water infiltration and increases erosion losses.

As the surface seal dries, it forms a hard **crust** (Figure 4.40). Seedlings, if they emerge at all, can do so only through cracks in the crust. Formation of a crust soon after a crop is

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Figure 4.39 *Contrasting tillage systems. (*Left*) A moldboard plow slices, twists, and partially inverts the plow layer of soil, burying all plant residues and leaving the soil uncovered. (*Right*) A conservation tillage system in which tomato seedlings are being transplanted into a mulch of killed cover crop residue with almost no soil disturbance at all. This no-tillage system keeps a residue cover on the soil at all times, protects the soil from erosion, reduces fuel costs, saves time, and allows operations to proceed under conditions that would be prohibitive if tillage were required. In this case the no-till transplanter is operating in the rain with no problems of compaction and mud. The black lines are irrigation tubing being lain down.* (Left photo courtesy of Ray R. Weil. Right photo courtesy of Steve Groff)

sown may allow so few seeds to emerge that the crop has to be replanted. In arid and semiarid regions, soil sealing and crusting can have disastrous consequences because high runoff losses leave little water available to support plant growth.

Crusting can be minimized by keeping some vegetative or mulch cover on the land to reduce the impact of raindrops. Once a crust has formed, it may be necessary to rescue a newly planted crop by breaking up the crust with light tillage (as with a rotary hoe), preferably while the soil is still moist.

Soil Conditioners

Improved management of soil organic matter and use of certain soil amendments can "condition" the soil and help prevent clay dispersion and crust formation (see also Section 10.10).

Gypsum. Gypsum (calcium sulfate) is widely available in its relatively pure mined form, or as a major component of various industrial byproducts. Gypsum has been shown effective in improving the physical condition of many types of soils, from some highly weathered acid

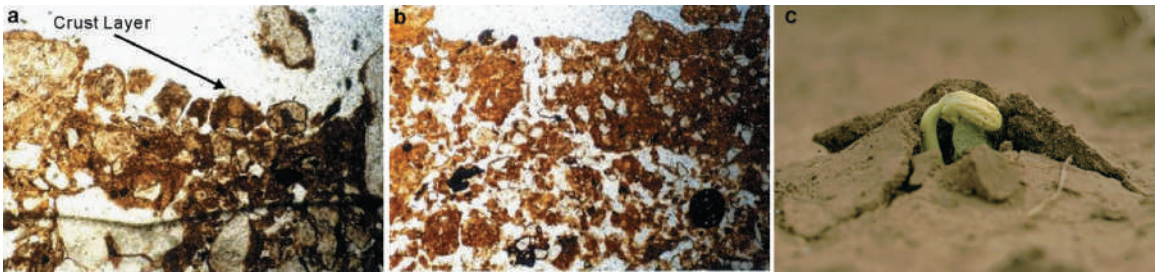

Figure 4.40 *Physical soil crusts. (a) Vertical section of the surface 3 mm of an Alfisol (yellow-brown soil in Chinese classification) with sandy loam texture from Hubei Province, China, exhibiting a typical crusted surface condition (a) and a noncrusted surface condition (b). The crust in (a) formed after the soil was exposed to 15 minutes of heavy rain. Note that the aggregates in the immediate surface have been destroyed, the fine particles have been washed downward, and the coarse particles near the surface have become tightly packed with few pores (white areas). A bean seedling (c) struggles to break a soil crust as it emerges from a seedbed.* [Photos (a) and (b) from Hu Xia; Shunjiangli; photo (c) courtesy of Ray R. Weil]

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soils to some low-salinity, high-sodium soils of semiarid regions (see Chapter 10). The more soluble gypsum products provide enough electrolytes (dissolved cations and anions) to promote flocculation and inhibit the dispersion of aggregates, thus preventing surface crusting. Field trials have shown that gypsum-treated soils permit greater water infiltration and are less subject to erosion than untreated soils. Similarly, gypsum can reduce the strength of hard subsurface layers, thereby allowing greater root penetration and subsequent plant uptake of water from the subsoil.

Organic Polymers. Certain synthetic organic polymers can stabilize soil structure in much the same way as do natural organic polymers such as polysaccharides. For example, polyacrylamide (PAM) is effective in stabilizing surface aggregates when applied at rates as low as 1–15 mg/L of irrigation water or sprayed on at rates as low as 1–4 kg/ha. Figure 4.41 shows the dramatic stabilizing effect of synthetic polyacrylamides used in irrigation water. Research indicates that combining the use of PAM and gypsum products can nearly eliminate irrigation-induced erosion.

Other Soil Conditioners. Several species of algae that live near the soil surface are known to produce quite effective aggregate-stabilizing compounds. Application of small quantities of commercial preparations containing such algae may bring about a significant improvement in surface soil structure. The amount of amendment required is very small because the algae, once established in the soil, can multiply.

Various "humate" materials are marketed as providing soil conditioning effects when incorporated at low rates (<500 kg/ha). However, carefully conducted research at many universities has failed to show that these materials have significantly affected aggregate stability or crop yield, as claimed.

General Guidelines for Managing Soil Tilth

Although each soil presents unique problems and opportunities, the following suggestions are generally relevant to managing soil tilth:

1. Minimizing tillage, especially moldboard plowing, disk harrowing, or rototilling, reduces the loss of aggregate-stabilizing organic matter.
2. Timing traffic activities to occur when the soil is as dry as possible and restricting tillage to periods of optimum soil moisture conditions will minimize destruction of soil structure.

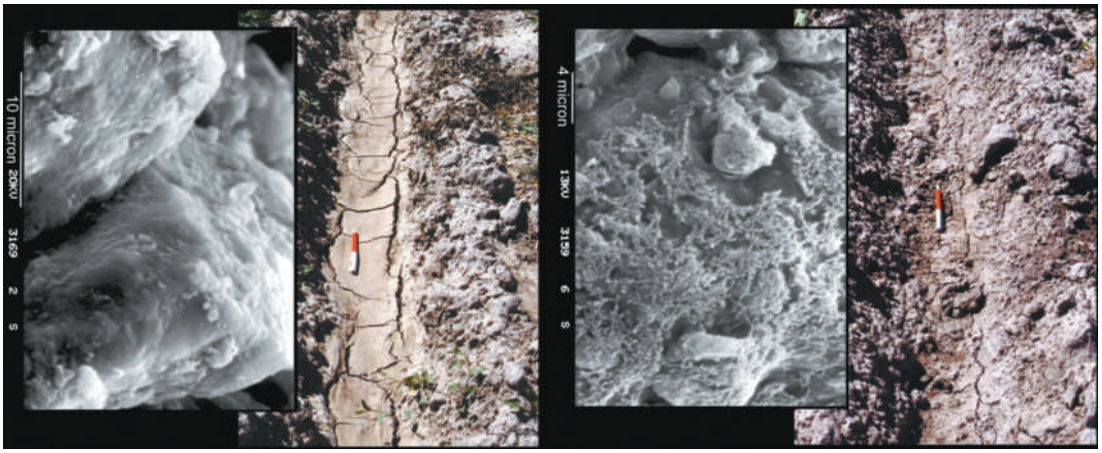

Figure 4.41 *The dramatic stabilizing effect of synthetic polyacrylamide (PAM), which was used at rates of 1–2 kg/ha per irrigation in the furrow shown at right, but not in the furrow on the left (note the marker pens for scale). PAM increases infiltration by 15%–50% on medium to fine textured soils. Scanning electron micrographs (scale on left edge) reveal the structure of the respective soils. Note the meshlike network of pam enveloping the treated soil particles. This pam weighs about 12–15 mg per mole of anionic, water soluble molecules.* [Ross CW, Sojka RE, Foerster JA 2003: Scanning electron micrographs of polyacrylamide-treated soil in irrigation furrows. Journal of Soil and Water Conservation 58(5); 327–331]

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3. Mulching the soil surface with crop residues or plant litter adds organic matter, encourages earthworm activity, and protects aggregates from beating rain and direct solar radiation.
4. Adding crop residues, composts, and animal manures to the soil is effective in stimulating microbial supply of the decomposition products that help stabilize soil aggregates.
5. Including sod crops in the rotation favors stable aggregation by helping to maintain soil organic matter, providing maximal aggregating influence of fine plant roots, and ensuring a period without tillage.
6. Using cover crops and green manure crops, where practical, provides another good source of root action and decomposable organic matter for structural management.
7. Applying gypsum by itself or in combination with synthetic polymers can be very useful in stabilizing surface aggregates, especially in irrigated soils.

A high degree of aggregation helps the soil to perform critical ecosystem functions because most of these functions are influenced by soil porosity and density, properties which we shall now consider.

4.7 SOIL DENSITY

Particle Density

Soil **particle density** D_p is defined as the mass per unit volume of soil *solids* (in contrast to the volume of the *soil*, which would also include spaces between particles). Thus, if 1 cubic meter (m^3) of soil solids weighs 2.6 megagrams (Mg), the particle density is 2.6 Mg/m^3 (which can also be expressed as 2.6 grams per cubic centimeter).[7]

Particle density is essentially the same as the **specific gravity** of a solid substance. The chemical composition and crystal structure of a mineral determines its particle density. Particle density is *not* affected by pore space, and therefore is not related to particle size or to the arrangement of particles (soil structure).

Particle densities for most mineral soils vary between the narrow limits of 2.60 and 2.75 Mg/m^3 because quartz, feldspar, micas, and the colloidal silicates that usually make up the major portion of mineral soils all have densities within this range. For general calculations concerning arable mineral surface soils (1%–5% organic matter), a particle density of about 2.65 Mg/m^3 may be assumed if the actual particle density is not known. This number would be adjusted upward to 3.0 Mg/m^3 or higher when large amounts of high-density minerals such as magnetite, garnet, epidote, zircon, tourmaline, or hornblende are present. Likewise, it would be reduced for soils known to be high in organic matter, which has a particle density of only 0.9–1.4 Mg/m^3.

Bulk Density

A second important mass measurement of soils is **bulk density** D_b, which is defined as the mass of a unit volume of dry soil. This volume includes both solids and pores. A careful study of Figure 4.42 should make clear the distinction between particle and bulk density. Both expressions of density use only the mass of the solids in a soil; therefore, any water present is excluded from consideration.

There are several methods of determining soil bulk density by obtaining a known volume of soil, drying it to remove the water, and weighing the dry mass.[8] A special coring instrument (Figure 4.43) can obtain a sample of known volume without disturbing the natural soil structure. For surface soils, perhaps the simplest method is to dig a small hole, dry and weigh all the excavated soil, and then determine the soil volume by lining the hole with plastic film and filling it completely with a measured volume of water. This method is well adapted to stony soils in which it is difficult to use a core sampler.

[7]Since 1 Mg = 1 million grams and 1 m^3 = 1 million cubic centimeters, 1 Mg/m^3 = 1 g/cm^3.
[8]An instrumental method that measures the soil's resistance to the passage of gamma rays is used in soil research, but is not discussed here.

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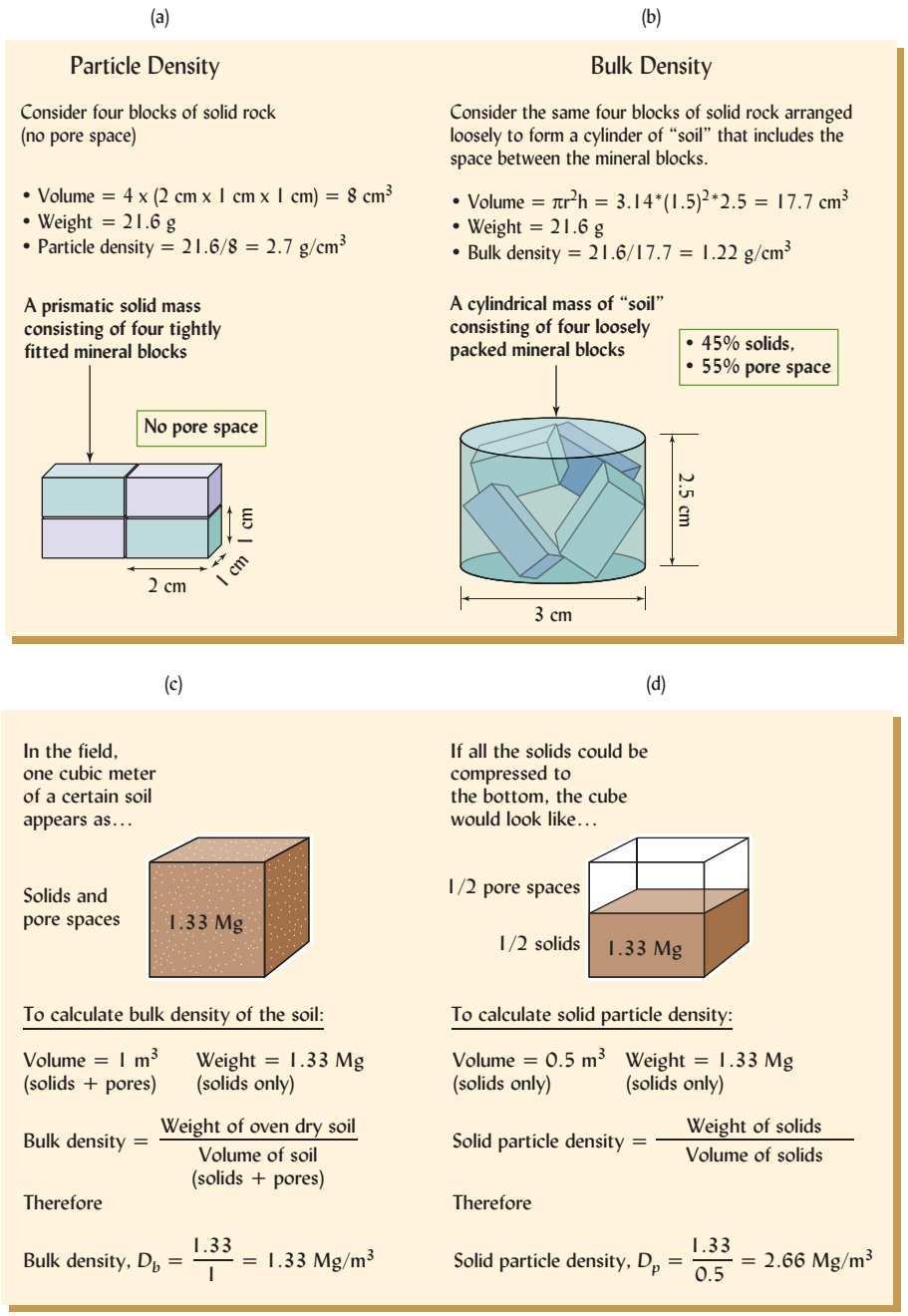

Figure 4.42 *Bulk density D_b and particle density D_p of soil. Particle density describes the weight of solid particles in a given volume of those solid particles, for example, the four blocks (particles) of solid rock stacked tightly with no pore space (a). Bulk density is the weight of the solid particles in a given volume of dry soil (which includes both solids plus pore space occupied by air). Consider the diagram of the same four blocks of rock, now loosely arranged inside a cylinder to form "soil" that includes both the solid blocks and the spaces between them (b). Follow the calculations carefully and the terminology should be clear. In this particular case (c,d) the bulk density is one-half the particle density, and the porosity is 50%.*
(Diagrams courtesy of Ray R. Weil)

Factors Affecting Bulk Density

Soils with a high proportion of pore space to solids have lower bulk densities than those that are more compact and have less pore space. Consequently, any factor that influences soil pore space will affect bulk density. Typical ranges of bulk density for various soil materials and conditions are illustrated in Figure 4.44. It would be worthwhile to study this figure until you have a good feel for these ranges of bulk density.

Effect of Soil Texture. As illustrated in Figure 4.44, fine-textured soils such as silt loams, clays, and clay loams generally have lower bulk densities than do sandy soils.[9] This is true

[9]This fact may seem counterintuitive at first because sandy soils are commonly referred to as "light" soils, while clays and clay loams are referred to as "heavy" soils. The terms *heavy* and *light* in this context refer not to the mass per unit volume of the soils, but to the amount of effort that must be exerted to manipulate these soils with tillage implements—the sticky clays being much more difficult to till.

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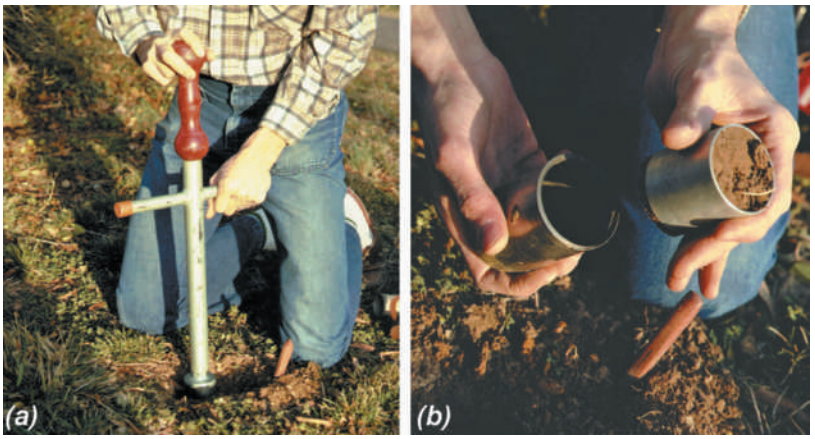

Figure 4.43 *A special sampler designed to remove a cylindrical core of soil without causing disturbance or compaction (a). The sampler head contains an inner cylinder and is driven into the soil with blows from a drop hammer. The inner cylinder (b) containing an undisturbed soil core is then removed and trimmed on the end with a knife to yield a core whose volume can easily be calculated from its length and diameter. The weight of this soil core is then determined after drying in an oven.* (Photos courtesy of Ray R. Weil)

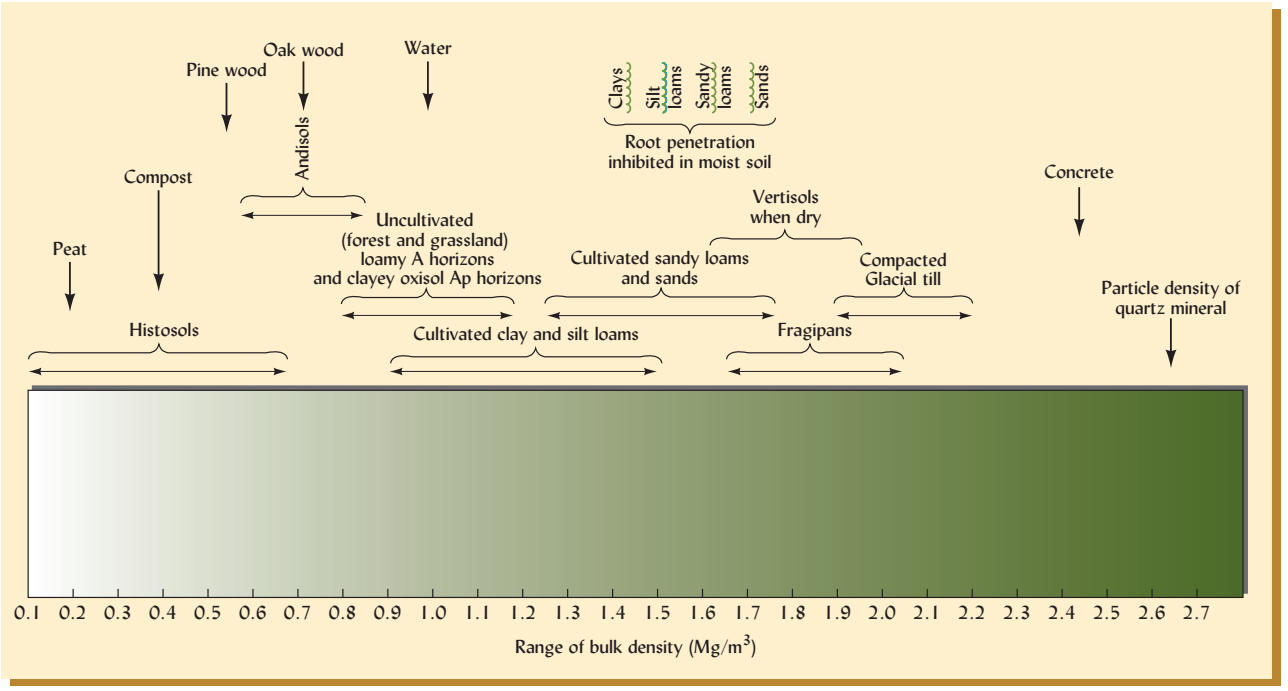

Figure 4.44 *Bulk densities typical of a variety of soils and soil materials.*

because the solid particles of the fine-textured soils tend to be organized in porous granules, especially if adequate organic matter is present. In these aggregated soils, pores exist both between *and* within the granules. This condition ensures high total pore space and a low bulk density. In sandy soil, however, organic matter contents generally are low, the solid particles are less likely to be aggregated, and the bulk densities are commonly higher than in the finer-textured soils. Similar amounts of large pores are present in both sandy and well-aggregated fine-textured soils, but sandy soils have few of the fine, within-ped pores, and so have less total porosity (Figure 4.45).

While sandy soils generally have high bulk densities, the packing arrangement of the sand grains also affects their bulk density (see Figure 4.46). Loosely packed grains may fill as little as 52% of the bulk volume, while tightly packed grains may fill as much as 75% of the volume. If we assume that grains consist of quartz with a particle density of 2.65 Mg/m^3, then the corresponding range of bulk densities for loose to tightly packed sand would be 1.38–1.99 Mg/m^3 not too different from the range actually encountered in very sandy soils. The bulk density is generally lower if the sand particles are mostly of one size class (i.e., *well-sorted* sand), while a mixture of different sizes (i.e., *well-graded* sand) is likely to have an especially high bulk

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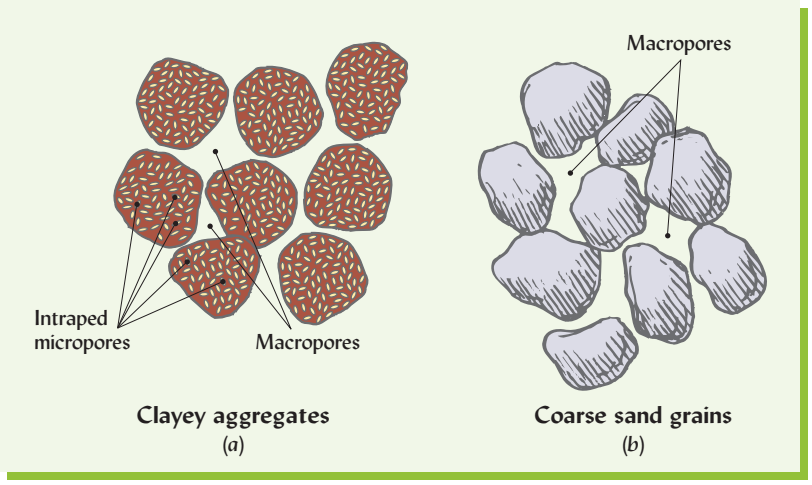

Figure 4.45 *A schematic comparison of sandy and clayey soils showing the relative amounts of large (macro-) pores and small (micro-) pores in each. There is less total pore space in the sandy soils than in the clayey one because the clayey soil contains a large number of fine pores within each aggregate (a), but the sand particles (b), while similar in size to the clayey aggregates, are solid and contain no pore spaces within them. This is the reason why, among surface soils, those with coarse texture are usually more denser than those with finer textures.* (Diagram courtesy of Ray R. Weil)

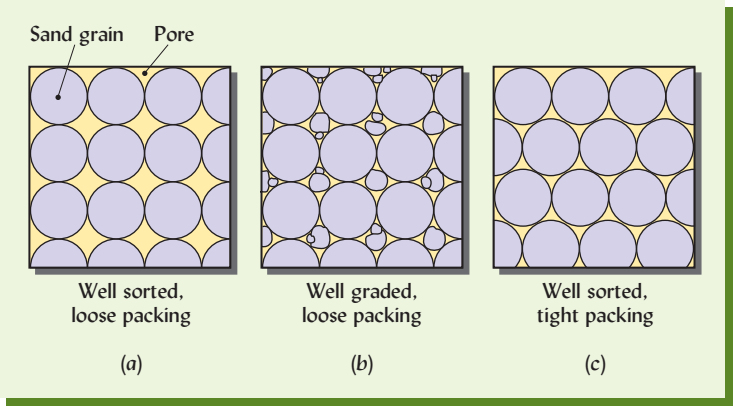

Figure 4.46 *The uniformity of grain size and the type of packing arrangement significantly affect the bulk density of sandy materials. Materials consisting of all similar-sized grains are termed* well sorted *(or poorly graded). Those with a variety of grain sizes are* well graded *(or poorly sorted). In either case, compaction of the particles into a tight packing arrangement markedly increases the bulk density of the material and decreases its porosity. Note that the size distribution of sand and gravel particles can be described as either graded or sorted, the two terms having essentially opposite meanings. Geologists usually speak of rivers having sorted the sand grains by size as deposits were laid down. Engineers usually are concerned as to whether or not sand consists of a gradation of sizes (i.e., is well graded or not).*

density. In the latter case, the smaller particles partially fill in the spaces between the larger particles. The most dense materials are those characterized by both a mixture of sand sizes and a tight packing arrangement.

Depth in Soil Profile. Deeper in the soil profile, bulk densities are generally higher, usually as a result of compaction caused by the weight of the overlying layers, lower organic matter contents, less aggregation, and fewer biopores. Very compact subsoils may have bulk densities of 2.0 Mg/m^3 or even greater. Many soils formed from glacial till (see Section 2.13) have extremely dense subsoils as a result of past compaction by the enormous masses of ice overlaying them.

Useful Density Figures

For engineers involved with moving soil during construction, or for landscapers bringing in topsoil by the truckload, knowledge of the bulk density of various soils is useful in estimating the weight of (dry!) soil to be moved. A typical medium-textured mineral soil might have a bulk density of 1.25 Mg/m^3, or 1250 kilograms in a cubic meter. People are often surprised by how heavy soil is. Imagine driving your pickup truck to a nursery where natural topsoil is sold in bulk and filling your truck bed (1.8 m $\times$ 2.4 m) with a nice, rounded load of about

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4.3 m^3. Of course, you would not really want to do this, as you certainly would not be able to drive away with the load. A typical "half-ton" (1000 lb or 454 kg) pickup truck load capacity would be equivalent to 0.36 m^3 of this soil (less if the soil were moist), even though the truck bed has room for about 12 times this volume of material.

The mass of soil in 1 ha to a depth of normal plowing (15 cm) can be calculated from soil bulk density. If we assume a bulk density of 1.3 Mg/m^3 for a typical arable surface soil, such a hectare-furrow slice 15 cm deep weighs about 2 million kg.[10] This estimate of the mass of surface soil in a hectare of land is very useful in calculating lime and fertilizer application rates and organic matter mineralization rates (see Boxes 8.4, 9.4, 10.4, and 13.1 for detailed examples). However, this estimated mass should be adjusted if the bulk density is other than 1.3 Mg/m^3 or the depth of the layer under consideration is more or less than 15 cm.

Management Practices Affecting Bulk Density

Changes in bulk density for a given soil are easily measured and can alert soil managers to changes in soil quality and ecosystem function. Increases in bulk density usually indicate a poorer environment for root growth, reduced aeration, and undesirable changes in hydrologic function, such as reduced water infiltration.

Forest Lands. The surface horizons of most forested soils have rather low bulk densities (see Figure 4.44). Tree growth and forest ecosystem function are particularly sensitive to increases in bulk density. Conventional timber harvest generally disturbs and compacts 20%–40% of the forest floor (Figure 4.47) and is especially damaging along the skid trails where logs are dragged and at the landing decks—areas where logs are piled and loaded onto trucks (Table 4.3). An expensive, but effective, means of moving logs while minimizing compactive degradation of forest lands is the use of cables strung between towers or hung from large balloons.

Intensive recreational and transport use of soils in forests and other areas with natural vegetation can also lead to increased bulk densities. Such effects can be seen where access roads, trails, and campsites are found (Figure 4.48). An important consequence of increased bulk density is a diminished capacity of the soil to take in water, hence increased losses by surface runoff. Damage from hikers can be minimized by restricting foot traffic to well-designed, established trails that may include a thick layer of wood chips, or even a raised boardwalk in the case of heavily traveled paths over very fragile soils, such as in wetlands.

Figure 4.47 *Timber harvest can compact forest soils.* (Left) *Heavy equipment (a skidder and logging truck) at a landing deck where the soil is severely impacted under wet conditions in a Southern Appalachian hardwood forest in the United States.* (Right) *A similar conventional rubber-tired skidder in a boreal forest in western Alberta, Canada. Such practices cause significant soil compaction that can impair soil ecosystem functions for many years. Timber harvest practices that can reduce such damage to forest soils include selective cutting, use of flexible-track vehicles or overhead cable transport of logs, and abstaining from harvest during wet conditions.* [Photos courtesy of Ray R. Weil (*left*) and Andrei Startsev, Alberta Environmental Center, (*right*)]

[10] 10,000 m^2/ha × 1.3 Mg/m^3 × 0.15 m = 1950 Mg/ha, or about 2 million kg per ha to a depth of 15 cm. A comparable figure in the English system is 2 million lb per acre—furrow slice 6–7 in. deep.

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Table 4.3
EFFECTS OF TIMBER HARVEST ON BULK DENSITY AT DIFFERENT DEPTHS IN TWO FORESTED ULTISOLS IN GEORGIA
Rubber-wheeled skidders were used to harvest the logs. Note the generally higher bulk densities of the sandy loam soil compared to the clay loam, and the greater effect of timber harvest on the skidder trails.

	Bulk density, Mg/m^3		
Soil depth, cm	**Preharvest**	**Postharvest, off trails**	**Postharvest, skidder trails**
Upper coastal plain, sandy loam			
0–8	1.25	1.50	1.47
8–15	1.40	1.55	1.71
15–23	1.54	1.61	1.81
23–30	1.58	1.62	1.77
Piedmont, clay loam			
0–8	1.16	1.36	1.52
8–15	1.39	1.49	1.67
15–23	1.51	1.51	1.66
23–30	1.49	1.46	1.61

Data from Gent et al. (1984, 1986).

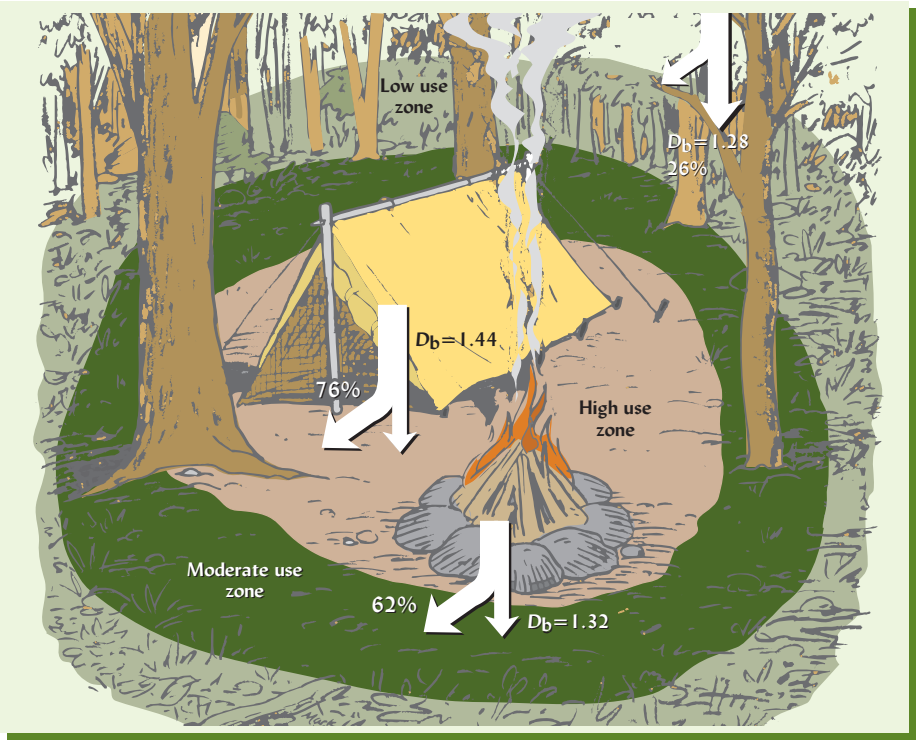

Figure 4.48 *Impact of campers on the bulk density of forest soils, and the consequent effects on rainwater infiltration rates and runoff losses (see white arrows). At most campsites the high impact area extends for about 10 m from the fire circle or tent pad. Managers of recreational land must carefully consider how to protect sensitive soils from compaction that may lead to death of vegetation and increased erosion.* [Data from Vimmerstadt et al. (1982)]

Urban Soils. In urban areas, trees planted for landscaping purposes must often contend with severely compacted soils. While it is usually not practical to modify the entire root zone of a tree, several practices can help (see also Section 7.6). First, making the planting hole as large as possible will provide a zone of loose soil for early root growth. Second, a thick layer of mulch spread out to the drip line (but not too near the trunk) will enhance root growth, at least near the surface. Third, a rigid but porous cover, such as an iron grill, can be installed around the

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Figure 4.49 *A cast iron grill designed to protect a young urban tree root zone from compaction by foot traffic while allowing rain water and air to readily penetrate into the root zone. The concentric circles of grillwork are designed to be broken off to enlarge the trunk hole before girdling can occur. unfortunately, in this case maintenance has been lax, so the trunk has outgrown the hole and the grill is starting to girdle the tree.* (Photo courtesy of Ray R. Weil)

tree to protect against compaction while letting in water and air (Figure 4.49). Fourth, the tree roots may be given paths for expansion by digging a series of narrow trenches radiating out from the planting hole and backfilled with loose, enriched soil.

In some urban settings, it may be desirable to create an "artificial soil" that includes a skeleton of coarse angular gravel to provide strength and stability, and a mixture of loam-textured topsoil and organic matter to provide nutrient- and water-holding capacities. Also, large quantities of sand and organic materials are sometimes mixed into the upper few centimeters of a fine-textured soil on which putting green turf grass is to be grown.

Green Roofs. Soil bulk density is critical in the design of rooftop gardens. The mass of soil involved must be minimized in order to design a cost-effective structure of sufficient strength to carry the soil load. One might choose to grow only such shallow-rooted plants as sedums or turf grasses so that a relatively thin layer of soil (say, 15 cm) could be used, keeping the total mass of soil from being too great. It may also be possible to reduce the cost of construction by selecting a natural soil having a relatively low bulk density, such as some well-aggregated loams or peat soils. Often an artificial growing medium is created from such lightweight materials as perlite and peat. However, such very low-density materials may require a surface netting system to prevent wind from blowing them off the roof, and this type of media will not perform the anchorage function of soils as a plant medium (see Section 1.2) for tall plants such as trees.

Agricultural Land. Although tillage may temporarily loosen the surface soil, in the long-term intense tillage increases soil bulk density by depleting soil organic matter and weakening soil structure (see Section 4.6). The data in Table 4.4 illustrate this trend. These data are from long-term studies in different locations where relatively undisturbed soils were compared to adjacent areas that had been cultivated for 12 to 80+ years. In all cases, cropping increased the bulk density of the topsoils. The effect of cultivation can be minimized by adding crop residues or farm manure in large amounts and rotating cultivated crops with a grass sod.

In mechanized agriculture, the wheels of heavy machines used to pull implements, apply amendments, or harvest crops can create yield-limiting soil compaction. Certain tillage implements, such as the moldboard plow and the disk harrow, compact the soil below their working depth even as they lift and loosen the soil above. Use of these implements or repeated trips over the field by heavy machinery can form **plow pans** or **traffic pans**, dense zones immediately below the plowed layer (Figure 4.50). Other tillage implements, such as the chisel plow and the spring-tooth harrow, do not press down upon the soil beneath them, and so are

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Table 4.4
BULK DENSITY AND PORE SPACE OF SURFACE SOILS FROM CULTIVATED AND NEARBY UNCULTIVATED AREAS
With cultivation, the bulk density was increased, and the pore space proportionately decreased, in every case.

			Bulk density, Mg/m^3		Pore space, %	
Soil	Texture	Years cropped	Cultivated soil	Uncultivated soil	Cultivated soil	Uncultivated soil
Mean of 6 Ustolls (South Dakota, USA)	Silt loam	80+	1.30	1.10	50.9	58.5
Mean of 2 Udults (Maryland, USA)	Sandy loam	50+	1.59	0.84	40.0	66.4
Mean of 2 Udults (Maryland, USA)	Silt loam	50+	1.18	0.78	55.5	68.8
Xeroll (Turkey)	Clay loam	12	1.34	1.25	49.6	52.7
Mean of 3 Ustalfs (Zimbabwe)	Clay	20–50	1.44	1.20	54.1	62.6
Mean of 3 Ustalfs (Zimbabwe)	Sandy loam	20–50	1.54	1.43	42.9	47.2

Data for South Dakota soils from Eynard et al. (2004), for Turkey from Celik (2005), for Maryland from Lucas and Weil (2012), and for Zimbabwe from Weil (unpublished).

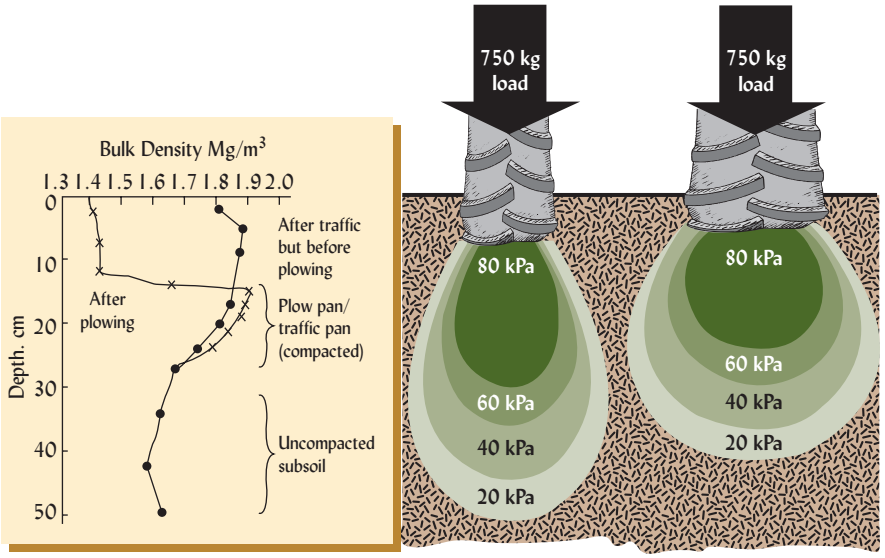

Figure 4.50 *Vehicle tires compact soil to considerable depths.* (Left) *Representative bulk densities associated with traffic compaction on a sandy loam soil. Plowing can temporarily loosen the compacted surface soil (plow layer), but usually increases compaction just below the plow layer.* (Right) *Vehicle tires (750 kg load per tire) compact soil to about 50 cm. The more narrow the tire, the deeper it sinks and the deeper its compactive effect. The tire diagram shows the compactive pressure in kPa. For tire designs that reduce compaction, see Tijink and Van der Linden (2000).* (Diagrams courtesy of Ray R. Weil)

useful in breaking up plow pans and stirring the soil with a minimum of compaction. Large chisel-type plows (Figure 4.51*a*) can be used in **subsoiling** to fracture soils to considerable depth and break up dense subsoil layers, thereby enhancing deep root penetration (Figure 4.51*b*). These implements should loosen the soil without producing horizontal compacted layers, and cut through crop residues while causing little disturbance of the soil surface. However, in most soils the effects of subsoiling are quite temporary and any tillage tends to reduce soil strength, thus making the soil less resistant to subsequent compaction. In moist fine-textured soils, subsoiling can cause planes of compaction as the implements slide through the soil.

In cold climates, repeated cycles of freezing and thawing during winter can break up compacted soil near the surface. However, even where it is cold enough to freeze the soil down to 50 or 100 cm, the repeated freeze–thaw cycles occur only on the upper 10–20 cm. Thus,

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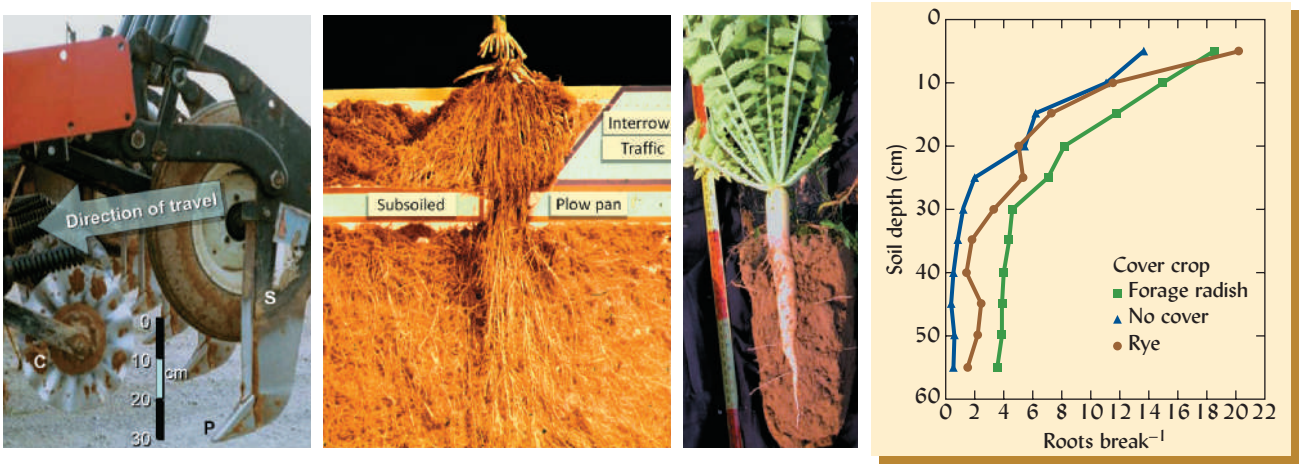

Figure 4.51 *Two approaches to the alleviation of subsoil compaction. (a) A heavy chisel plow, also known as a subsoiler or ripper. The heavy shanks (S) are pulled through the soil toward the left with the chisel point (P) about 40 cm deep. If the soil is relatively dry, the subsoiler will cause the mass of compacted soil to shatter leaving a network of cracks that enhance water, air, and root movement (b). However, pulling a subsoiler through dry, clayey soil is a slow, energy-intensive operation, the benefits usually last for only a year or two, and the operation usually disturbs the soil surface, leaving it more susceptible to erosion. Recently, researchers in humid regions have investigated an alternative approach that involves growing taprooted plants (such as the forage radish shown) in the fall and spring when the subsoil is relatively wet and easily penetrated by roots (c). The taproots then decay, leaving semipermanent channels in which roots of subsequent crops can grow to pass through the compacted subsoil zone, even during the summer when the soil is relatively dry and hard. (d) Corn planted after forage radish had twice as many roots reaching the subsoil (below 30 cm) as corn planted after the fibrous rooted rye, and nearly ten times as many as corn planted in soil that had no cover crop during the winter.* [Photos (a) and (c) courtesy of Ray R. Weil, photo (b) courtesy of USDA National Tillage Laboratory, data based on study by Chen and Weil (2011)]

if heavy equipment driven on wet soils have cause deep compaction, one cannot rely on cold winters to alleviate the problem.

Certain plants have been shown to alleviate deep subsoil compaction. A recently developed alternative to deep tillage is the use of cover crop plants which can penetrate compacted layers during moist periods and leave deep root channels for subsequent crops' roots to follow (Figure 4.51*c,d*). Species with thick taproots are best suited to this use.

In many parts of the world, farmers use hand hoes or animal-drawn implements to stir the soil. Although humans and draft animals are not as heavy as tractors, their weight is applied to the soil in a relatively small area (foot- or hoof-print), and so can also cause considerable compaction.

Traffic is particularly damaging on wet soil. Generally, with heavier loads and on wetter soils, compactive effects are more pronounced and penetrate more deeply into the profile. To prevent compaction, which can result in yield reductions and loss of profitability, the number of tillage operations and heavy equipment trips over the field should be minimized and timed to avoid periods when the soil is wet. Unfortunately, traffic on wet agricultural soils is sometimes unavoidable in humid temperate regions in spring and fall.

Another approach for minimizing compaction is to carefully restrict all wheel traffic to specific lanes, leaving the rest of the field (usually 90% or more of the area) free from compaction. Such **controlled traffic** systems are widely used in Europe, especially on clayey soils. Gardeners can practice controlled traffic by establishing permanent footpaths between planting beds. The paths may be enhanced by covering with a thick mulch, planting to sod grass, or paving with flat stones.

Some managers attempt to reduce compaction using an opposite strategy in which special wide tires are fitted to heavy equipment so as to spread the weight over more soil surface, thus reducing the force applied per unit area (Figure 4.52). Wider tires do lessen the compactive effect, but they also increase the percentage of the soil surface that is impacted. In a practice analogous to using wide wheels, home gardeners can avoid concentrating their body weight on just the few square centimeters of their footprints by standing on wooden boards when preparing seedbeds in relatively wet soil (Figure 4.52, *inset*).

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Figure 4.52 *One approach to reducing soil compaction is to spread the applied weight over a larger area of the soil surface. Examples are extra-wide wheels on heavy vehicles used to apply soil amendments (right) and standing on a wooden board while preparing a garden seedbed in early spring (inset).* (Photos courtesy of Ray R. Weil)

Influence of Bulk Density on Soil Strength and Root Growth

High bulk density may occur as a natural soil profile feature (e.g., a fragipan), or it may be an indication of human-induced soil compaction. In any case, root growth is inhibited by excessively dense soils for a number of reasons, including the soil's resistance to penetration, poor aeration, slow movement of nutrients and water, and the buildup of toxic gases and root exudates.

Roots penetrate the soil by pushing their way into pores. If a pore is too small to accommodate the root cap, the root must push the soil particles aside and enlarge the pore. To some degree, the density per se restricts root growth, as the roots encounter fewer and smaller pores. However, root penetration is also limited by **soil strength**, the property of the soil that causes it to resist deformation. One way to quantify soil strength is to measure the force needed to push a standard shaped rod (a **penetrometer**) into the soil (see also Section 4.9). Compaction generally increases both bulk density and soil strength. At least two factors (both related to soil strength) must be considered to determine the effect of bulk density on the ability of roots to penetrate soil.

Effect of Soil Water Content. Soil water content and bulk density both affect *soil strength* (see Section 4.9 and Figure 4.53). Soil strength is increased when a soil is compacted to a higher bulk density, and also when finer-textured soils dry out and harden. Therefore, the effect of bulk density on root growth is most pronounced if those soils are dry, a higher bulk density being necessary to prevent root penetration when the soils are moist. For example, a traffic pan having a bulk density of 1.6 Mg/m^3 may completely prevent the penetration of roots when the soil is rather dry, yet roots may readily penetrate this same layer when it is in a moist condition.

Effect of Soil Texture. The more clay present in a soil, the smaller the average pore size, and the greater the resistance to penetration at a given bulk density. Therefore, if the bulk density is the same, roots more easily penetrate a moist sandy soil than a moist clayey one. The growth of roots into moist soil is generally limited by bulk densities ranging from 1.45 Mg/m^3 in clays to 1.85 Mg/m^3 in loamy sands (see Figure 4.44). Viewed in this context, root growth was probably inhibited by the bulk density of the skidder trails in both soils illustrated in Table 4.3.

Effect of Land Use and Management. As might be expected, such land uses as row-crop agriculture, pasture, rangeland, forestry, or off-road trafficking often markedly and

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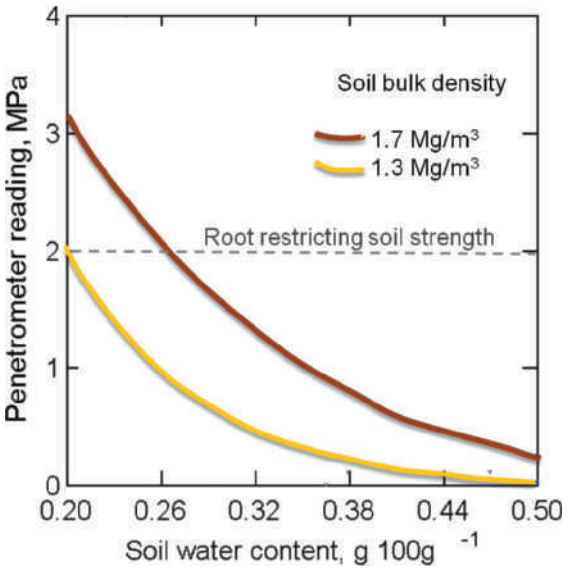

Figure 4.53 *Both water content and bulk density affect soil strength as measured by penetrometer resistance. The data are for the clay textured bt horizon of a tatum soil in Virginia, USA (Hapludults), which was either severely compacted (bulk density 1.7 Mg/m^3) or not compacted (bulk density 1.3 Mg/m^3). Note that soil strength decreases as water content increases and is very low regardless of bulk density when the soil is nearly saturated with water.* (Graph based on study by Gilker et al. (2002))

simultaneously affect soil bulk density and strength in ways that restrict or enhance root growth and water movement. It is not always appreciated that tillage and traffic can cause compaction quite deep into the subsoil. It may take many years of restorative management for the subsoil to recover its natural degree of porosity and friability. Figure 4.54 illustrates such a case.

4.8 PORE SPACE OF MINERAL SOILS[11]

One of the main reasons for measuring soil bulk density is that this value can be used to calculate pore space. For soils with the same particle density, the lower the bulk density, the higher the percent pore space (**total porosity**). See Box 4.6 for derivation of the formula expressing this relationship.

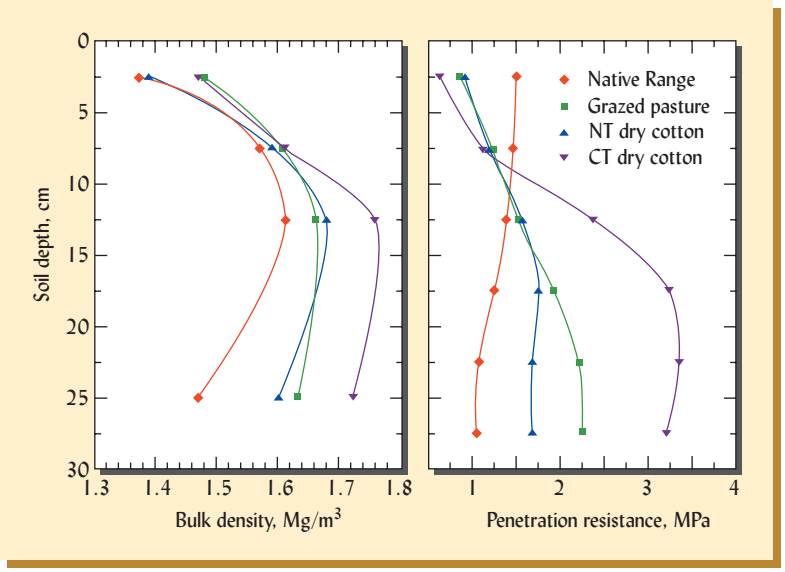

Figure 4.54 *Bulk density and penetration resistance after about 30 years of no-till (NT) and conventional tillage (CT) dryland cotton, or 15 years of grazed pasture compared to native rangeland. Conventional tillage cotton resulted in the greatest bulk density and penetration resistance, especially below the depth of plowing (15–20 cm), suggesting the formation of a plow pan in the ct cotton soil. After 15–30 years without tillage, the pasture and no-till cotton systems had partially recovered the favorable physical properties of the native rangeland. The penetration resistance levels for all systems were quite high (2 mpa can restrict root growth) because water contents of these semiarid region soils were quite low at the time of measurement. However, soil water was relatively uniform among the systems, at least in the lower layers where the major differences in penetration resistance occurred. Amarillo loamy fine sand (Aridic Paleustalfs) in the southern high plains of Texas, USA.* (Drawn from data in Halfmann (2005))

[11]For a review of how soil pores interact with hydrology, see Lin (2012).

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BOX 4.6

CALCULATION OF PERCENT PORE SPACE IN SOILS

The bulk density of a soil can be easily measured and particle density can usually be assumed to be 2.65 Mg/m^3 for most silicate-dominated mineral soils. Direct measurement of the pore space in soil requires the use of much more tedious and expensive techniques. Therefore, when information on the percent pore space is needed, it is often desirable to calculate the pore space from data on bulk and particle densities.

The derivation of the formula used to calculate the percentage of total pore space in soil follows:

Let D_b = bulk density, Mg/m^3

D_p = particle density, Mg/m^3

W_s = Weight of soil (solids), Mg

V_s = volume of solids, m^3

V_p = volume of pores, m^3

$V_s + V_p$ = total soil volume V_t

By definition,

$$\frac{W_s}{V_s} = D_p \quad \text{and} \quad \frac{W_s}{V_s + V_p} = D_b$$

Solving for W_s gives

$$W_s = D_p \times V_s \quad \text{and} \quad W_s = D_b(V_s + V_p)$$

Therefore

$$D_p \times V_s = D_b(V_s + V_p) \quad \text{and} \quad \frac{V_s}{V_s + V_p} = \frac{D_b}{D_p}$$

Since

$$\frac{V_s}{V_s + V_p} \times 100 = \text{\% solid space} \quad \text{then}$$

$$\text{\% solid space} = \frac{D_b}{D_p} \times 100$$

Since % pore space + % solid space = 100%, and % pore space, % then

$$\text{pore space} = 100\% - \left(\frac{D_b}{D_p} \times 100\right)$$

EXAMPLE

Consider a cultivated clay soil with a bulk density determined to be 1.28 Mg/m^3. If we have no information on the particle density, we assume that the particle density is approximately that of the common silicate minerals (i.e., 2.65 Mg/m^3). We calculate the percent pore space using the formula derived above:

$$\text{\% pore space} = 100\% - \left(\frac{1.28\ Mg/m^3}{2.65\ Mg/m^3} \times 100\right)$$

$$= 100\% - 48.3 = 51.7$$

This value of pore space, 51.7%, is quite close to the typical percentage of air and water space described in Figure 1.18 for a well-granulated, medium- to fine-textured soil in good condition for plant growth. This simple calculation tells us nothing about the relative amounts of large and small pores, however, and so must be interpreted with caution.

For certain soils it is inaccurate to assume that the soil particle density is 2.65 Mg/m^3. For instance, a soil with a high organic matter content can be expected to have a particle density somewhat lower than 2.65. Similarly, a soil rich in iron oxide minerals will have a particle density greater than 2.65 because these minerals have particle densities as high as 3.5. As an example of the latter type of soil, let us con-sider the uncultivated clay soils from Zimbabwe (Ustalfs) described in Table 4.4. These are red-colored clays, high in iron oxides. The particle density for these soils was determined to be 3.21 Mg/m^3 (not shown in Table 4.4. Using this value and the bulk density value from Table 4.4, we calculate the pore space as follows:

$$\text{\% pore space} = 100\% - \left(\frac{1.20}{3.21} \times 100\%\right)$$

$$= 100 - 37.4 = 62.6$$

Such a high percentage pore space is an indication that this soil is in an uncompacted, very well-granulated condition typical for soils found under undisturbed natural vegetation.

Factors Influencing Total Pore Space

In Chapter 1 (Figure 1.18) we noted that for an "ideal" medium-textured, well-granulated surface soil in good condition for plant growth, approximately 50% of the soil volume would consist of pore space, and that the pore space would be about half-filled with air and half-filled with water. Actually, total porosity varies widely among soils for the same reasons that bulk density varies. Values range from as low as 25% in compacted subsoils to more than 60% in well-aggregated, high-organic-matter surface soils. As is the case for bulk density, management can exert a decided influence on the pore space of soils (see Table 4.4). Data from a wide range of soils show that cultivation tends to lower the total pore space compared to that of uncultivated soils. This reduction usually is associated with a decrease in organic matter content and a consequent lowering of **granulation**.

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Size of Pores

Bulk density values help us predict only *total* porosity. However, soil pores occur in a wide variety of sizes and shapes that largely determine what role the pore can play in the soil. Pores can be grouped by size into macropores, mesopores, micropores, and so on (Table 4.5 illustrates one such grouping). We will simplify our discussion at this point by referring only to **macropores** (larger than about 0.08 mm) and **micropores** (smaller than about 0.08 mm).

Macropores. The macropores characteristically allow the ready movement of air and the drainage of water. They also are large enough to accommodate plant roots and the wide range of tiny animals that inhabit the soil (see Chapter 11). Several types of macropores are illustrated in Figure 4.55.

Macropores can occur as the spaces between individual sand grains in coarse-textured soils. Thus, even though a sandy soil has relatively low total porosity, the movement of air and water through such a soil is surprisingly rapid because of the dominance of the macropores.

In well-structured soils, the macropores are generally found between peds. These **interped pores** may occur as spaces between loosely packed granules or as the planar cracks between tight-fitting blocky and prismatic peds (see Figure 4.55*d*).

Macropores created by roots, earthworms, and other organisms constitute a very important type of pores termed **biopores**. These are usually tubular in shape and may be continuous for lengths of a meter or more (see Figure 4.26). In some clayey soils, biopores are the principal form of macropores, greatly facilitating the growth of plant roots (Table 4.6, Figure 4.26). Perennial plants, such as forest trees and certain forage crops, are particularly effective at creating channels that serve as conduits for roots, long after the death and decay of the roots that originally created them. Two such old root channels, each about 8 mm in diameter, can be seen perforating the clay slickenside shown in Figure 3.31*c*.

It is clear that both soil structure and texture influence the balance between macropores and micropores in a soil. Figure 4.56 shows that the decrease in organic matter and increase in clay that occur with depth in many profiles are associated with a shift from macropores to micropores.

Micropores. In contrast to macropores, micropores are usually filled with water in field soils. Even when not water-filled, they are too small to permit much air movement. Water movement

Table 4.5
A Size Classification of Soil Pores and Some Functions of Each Size Class
Pore sizes are actually a continuum and the boundaries between classes given here are inexact and somewhat arbitrary. The term **micropore** *is often broadened to refer to all the pores smaller than macropores.*

Simplified class	Class[a]	Effective diameter range, mm	Characteristics and functions
Macropores	Macropores	0.08–5+	Generally found between soil peds (interped); water drains by gravity; effectively transmit air; large enough to accommodate plant roots, habitat for certain soil animals.
Micropores	Mesopores	0.03–0.08	Retain water after drainage; transmit water by capillary action; accommodate fungi and root hairs.
	Micropores	0.005–0.03	Generally found within peds (intraped); retain water that plants can use; accommodate most bacteria.
	Ultramicropores	0.0001–0.005	Found largely within clay groupings; retain water that plants cannot use; exclude most microorganisms.
	Cryptopores	<0.0001	Exclude all microorganisms, too small for large molecules to enter.

[a]The pore size classes and boundary diameters are those cited in Soil Science Society of America (2001).

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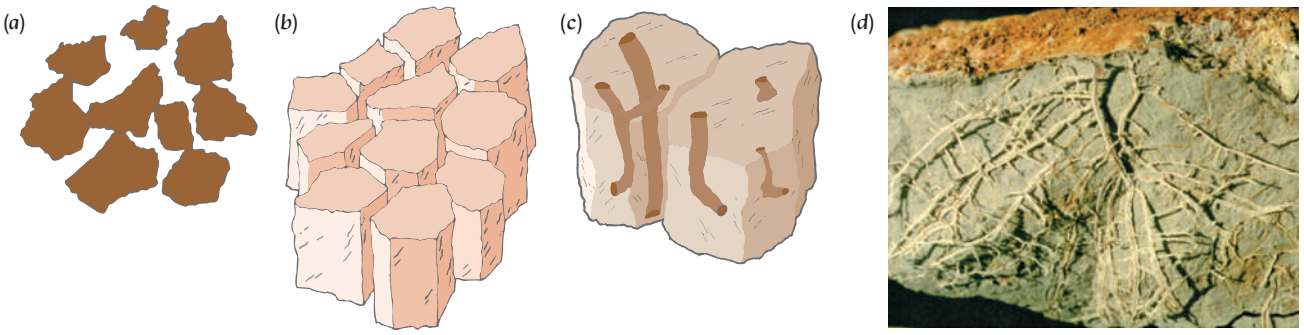

Figure 4.55 *Various types of soil pores. (a) Many soil pores occur as* packing pores, *spaces left between primary soil particles. The size and shape of these spaces is largely dependent on the size and shape of the primary sand, silt, and clay particles and their packing arrangement. (b) In soils with structural peds, the spaces between the peds form* interped pores. *These may be rather planar in shape, as with the cracks between prismatic peds, or they may be more irregular, like those between loosely packed granular aggregates. (c)* Biopores *are formed by organisms such as earthworms, insects, and plant roots. Most of these are long, sometimes branched channels, but some are round cavities left by insect nests and the like. (d) Plant roots proliferating along the face of a large prismatic ped in a fragipan. Note that the roots have become squeezed flat as the crack between adjacent prisms swelled closed during wet periods. No roots had penetrated the dense interior of the prism.* (Diagrams and photo courtesy of Ray R. Weil)

Table 4.6
DISTRIBUTION OF DIFFERENT-SIZED LOBLOLLY PINE ROOTS IN THE SOIL MATRIX AND IN OLD ROOT CHANNELS IN THE UPPERMOST METER OF AN ULTISOL IN SOUTH CAROLINA
The root channels were generally from 1 to 5 cm in diameter and filled with loose surface soil and decaying organic matter. Such channels are easy for roots to penetrate and have better fertility and aeration than the surrounding soil matrix.

	Numbers of roots counted per 1 m^2 of the soil profile		
Root size, diameter	**Soil matrix**	**Old root channels**	**Comparative increase in root density in the old channels, %**
Fine roots, <4 mm	211	3617	94
Medium roots, 4–20 mm	20	361	95
Coarse roots, >20 mm	3	155	98

Calculated from Parker and Van Lear (1996).

in micropores is slow, and much of the water retained in these pores is not available to plants (see Chapter 5). Fine-textured soils, especially those without a stable granular structure, may have a preponderance of micropores, thus allowing relatively slow gas and water movement, despite the relatively large volume of total pore space. Aeration, especially in the subsoil, may be inadequate for satisfactory root development and desirable microbial activity. While the larger micropores accommodate plant root hairs and microorganisms, the smaller micropores (sometimes termed *ultramicropores* and *cryptopores*) are so tiny that their radii are measured in nanometers (10^{-9} m), giving rise to the term *nanopores.* Such pores are too small to permit the entrance of even the smallest bacteria or some decay-stimulating enzymes produced by the bacteria. Thus, these pores can act as hiding places for some adsorbed organic compounds (both naturally occurring and pollutants), thereby protecting them from breakdown for long periods of time, perhaps for centuries (see Figure 18.18).

Clearly, the size, shape, and interconnection of soil pores, rather than their combined volume, are of greatest importance in determining soil drainage, aeration, and other such processes. Figure 4.55 illustrates the variability in size and shapes of the soil pores, which range from the micropores inside the aggregates where air and water movement is restricted, to the large macropores through which air and water will move freely.

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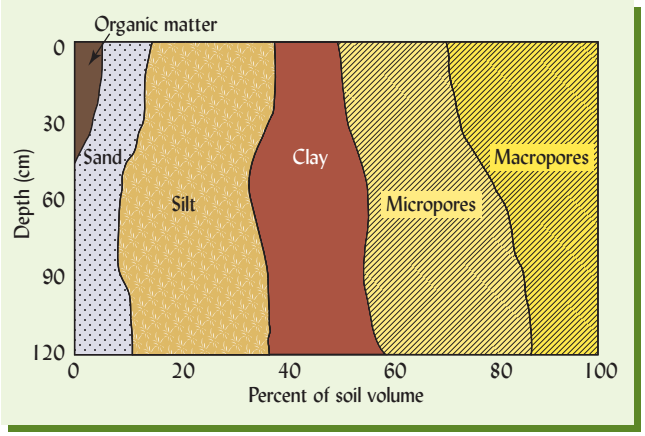

Figure 4.56 *Volume distribution of organic matter, sand, silt, clay, and pores of macro- and microsizes in a representative medium-textured soil with good structure. Note that macropores are especially plentiful in the surface horizon (upper 30 cm).* (Diagram courtesy of Ray R. Weil)

Cultivation and Pore Size

Continuous cropping, particularly of soils originally high in organic matter, often results in a reduction of macropore spaces (see Table 4.7). When native prairie lands are plowed and planted to row crops such as corn or soybeans, soil organic matter contents and total pore space are reduced. But most striking is the effect of cropping on the size of the soil pores. Such cropping drastically reduces the amount of macropore space that is so critical for ready air movement.

In recent years, conservation tillage practices, which minimize plowing and associated soil manipulations, have been widely adopted in the United States (see Sections 4.6 and 17.6). Because of increased accumulation of organic matter near the soil surface and the development of a long-lived network of macropores (especially biopores), some conservation tillage systems lead to greater macroporosity of the surface layers. These benefits are particularly likely to accrue in soils with extensive production of earthworm burrows, which may remain undisturbed in the absence of tillage. Unfortunately, such improvements in porosity do not always occur in soils with poor internal drainage.

4.9 SOIL PROPERTIES RELEVANT TO ENGINEERING USES

Soil properties are obviously important to engineering. In the words of Richard Hand:

> *Virtually every (built) structure is supported by soil or rock. Those that aren't either fly, float, or fall over.*

Table 4.7
CONTINUOUS CROPPING AFFECTS MACROPORE AND MICROPORE SPACES
Compared to undisturbed prairie soil, the cultivated soil has far less macropore space, but has gained some micropore space as aggregates were destroyed, changing large interped pores into much smaller micropores. Loss of organic matter made the aggregates more susceptible to damage by tillage. Houston clay (Hapludert).

Soil history	Soil depth, cm	Organic matter, %	Total pore space, %	Macropore space, %	Micropore space, %	Bulk density, Mg/m^3
Prairie	0–15	5.6	58.3	32.7	25.6	1.11
Tilled 50 years	0–15	2.9	50.2	16.0	34.2	1.33
Prairie	15–30	4.2	56.1	27.0	29.1	1.16
Tilled 50 years	15–30	2.8	50.7	14.7	36.0	1.31

Data from Laws and Evans (1949).

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Field Rating of Soil Consistence and Consistency

Consistence. Soil **consistence** is a term used by soil scientists to describe the ease with which a soil can be reshaped or ruptured. As a clod of soil is squeezed between the thumb and forefinger (or crushed underfoot, if necessary), observations are made on the amount of force needed to crush the clod and on the manner in which the soil responds to the force. The degree of cementation of the soil by such materials as silica, calcite, or iron is also considered in identifying soil consistence.

Moisture content greatly influences how a soil responds to stress; hence, moist and dry soils are given separate consistence ratings (Table 4.8). A dry, clayey soil that cannot be crushed between the thumb and forefinger but can be crushed easily underfoot would be designated as *very hard.* The same soil, when wet, would exhibit much less resistance to deformation, and would be termed *plastic*. The degrees of *stickiness* and *plasticity* (malleability) of soil in the wet condition are often included in describing soil consistence (although not shown in Table 4.8). As described in Section 4.6, a moist clod that crumbles with only light pressure is said to be friable. Friable soils are easily excavated or tilled.

Consistency. Engineers use the term **consistency** to describe how a soil resists *penetration* by an object, while the soil scientist's consistence describes resistance to *rupture.* Instead of crushing a

Table 4.8
SOME FIELD TESTS AND TERMS USED TO DESCRIBE THE CONSISTENCE AND CONSISTENCY OF SOILS
The consistency of cohesive materials is closely related to, but not exactly the same as, their consistence. Conditions of least coherence are represented by terms at the top of each column, those of greater coherence near the bottom.

Soil consistence[a]				Soil consistency[b]	
Dry soil	Moist to wet soil	Soil dried then submerged in water	Field rupture (crushing) test	Soil at in situ moisture	Field penetration test
Loose	Loose	Not applicable	Specimen not obtainable	Soft	Blunt end of pencil penetrates deeply with ease
Soft	Very friable	Noncemented	Crumbles under very slight force between thumb and forefinger	Medium firm	Blunt end of pencil can penetrate about 1.25 cm with moderate effort
Slightly hard	Friable	Extremely weakly cemented	Crumbles under slight force between thumb and forefinger	Firm	Blunt end of pencil can penetrate about 0.5 cm
Hard	Firm	Weakly cemented	Crushes with difficulty between thumb and forefinger	Very firm	Blunt end of pencil makes slight indentation; thumbnail easily penetrates
Very hard	Extremely firm	Moderately cemented	Cannot be crushed between thumb and forefinger, but can be crushed slowly underfoot	Hard	Blunt end of pencil makes no indentation; thumbnail barely penetrates
Extremely hard	Slightly rigid	Strongly cemented	Cannot be crushed by full body weight underfoot		

[a]Abstracted from USDA-NRCS (2005).
[b]Modified from McCarthy (1993).

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clod of soil, the engineer attempts to penetrate it with either the blunt end of a pencil (some use their thumbs) or a thumbnail. For example, if the blunt end of a pencil makes only a slight indentation, but the thumbnail penetrates easily, the soil is rated as *very firm* (Table 4.8). Consistency, then, is a kind of simple field estimation of soil strength or penetration resistance (see Section 4.7).

Field observations of both consistence and consistency provide valuable information to guide decisions about loading and manipulating soils. For construction purposes, however, more precise measurements are needed for related soil properties that help predict how a soil will respond to applied stress.

Soil Strength and Sudden Failure

Engineers define soil **bearing strength** as the capacity of a soil mass to withstand stresses without rupturing or becoming deformed. Failure of a soil to withstand stress can result in a building toppling over as its weight exceeds the soil's bearing strength. Similarly, an earthen dam or levee might give way under the pressure of impounded water, or pavements and structures might slide down unstable hillsides (see Figure 1.10).

Cohesive Soils. Two components of strength apply to **cohesive soils** (essentially soils with a clay content of more than about 15%): (1) the inherent electrostatic attractive forces between clay platelets and between clay surfaces and the water in very fine pores (see *clay flocculation* in Section 4.5), and (2) the frictional resistance to movement between soil particles of all sizes. While many different laboratory tests are used to estimate soil strength, perhaps the simplest to understand is the direct **unconfined compression test** using the apparatus illustrated in Figure 4.57*a*. A cylindrical specimen of cohesive soil is placed vertically between two flat, porous stones (which allow water to escape from the compressed soil pores) and a slowly increasing downward force is applied. The soil column will first bulge out a bit and then give way suddenly and collapse—when the force exceeds the soil strength.

The strength of clines dramatically if the material is very wet and the pores are filled with water. Then the particles are forced apart so that neither the cohesive nor the frictional component is very strong, making the soil prone to failure, often with dramatic results (such as mudslides and soil creep, Figure 4.58, or levee failures, Box 4.7). On the other hand, if cohesive soils become more compacted or dry down, their strength increases as particles are forced into closer contact with one another—a result that has implications for plant root growth as well as for engineering (see Section 4.7).

Noncohesive Soils. The strength of dry, noncohesive soil materials such as loose sand depends entirely on frictional forces, including the interlocking of rough particle surfaces. One reflection of such interparticle friction is the **angle of repose**, the steepest angle to which a material can be piled without slumping. Smooth, rounded sand grains cannot be piled as steeply as can rough, interlocking sands. If a small amount of water bridges the

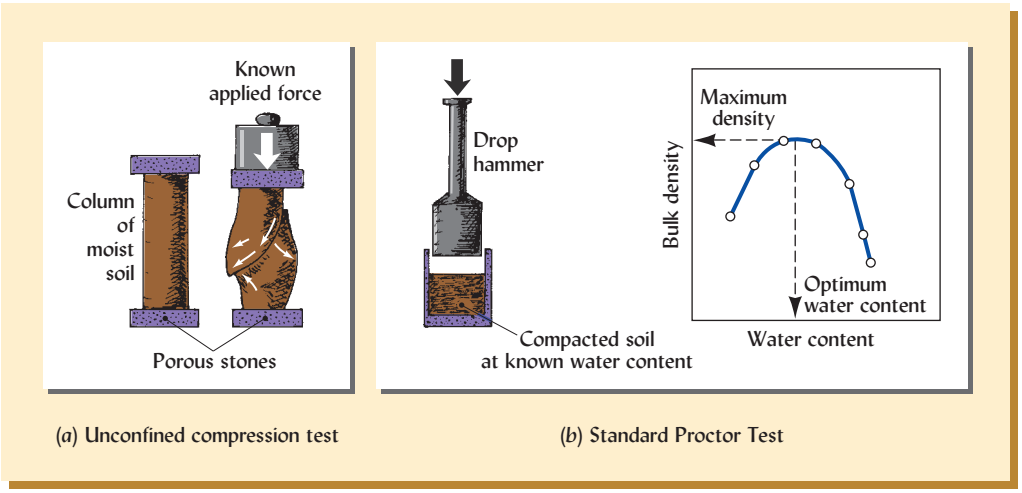

Figure 4.57 *Two important tests to determine engineering properties of soil materials.* (a) *An unconfined compression test for soil strength.* (b) *The Proctor test for maximum density and optimum water content for compaction control.*

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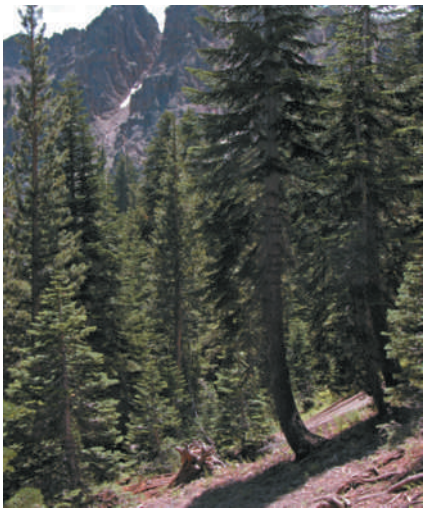

Figure 4.58 *As soils become wetter, both electrostatic and frictional components of soil strength may be reduced to the point that mass movement may occur either suddenly as in a mudslide* (left) *or very gradually as in soil creep* (right). *Mudslides occur when the soil becomes so wet as to behave almost as a liquid, flowing downslope, even over retaining walls. Soil creep is too slow to observe directly, but one can see the bowed tree trunks that result as the tree growth attempts to compensate for the downslope movement of soil.* (Photos courtesy of Ray R. Weil)

gaps between particles, electrostatic attraction of the water for the mineral surfaces will increase the soil strength (as illustrated in Figure 4.59). Interparticle water bridges explain why cars can drive along the edge of the beach where the sand is moist, but their tires sink in and lose traction on loose, dry sand or in saturated quicksand (see Figure 5.27 for an example of the latter).

Collapsible Soils. Certain soils that exhibit considerable strength at low *in situ* water contents lose their strength suddenly if they become wet. Such soils may collapse without warning under a roadway or building foundation. A special case of soil collapse is **thixotropy**, the sudden liquification of a wet soil mass when subjected to vibrations, such as those accompanying earthquakes and blasting.

Most **collapsible soils** are noncohesive materials in which loosely packed sand grains are cemented at their contact points by small amounts of gypsum, clay, or water under tension. These soils usually occur in arid and semiarid regions, where such cementing agents are relatively stable. Many collapsible soils have derived their open particle arrangement from the process of sedimentation beneath past or present bodies of water. When these soils are wetted, excess water may dissolve cements such as gypsum or disperse clays that form bridges between particles, causing a sudden loss of strength. In some cases, similar behavior is exhibited by highly weathered Oxisols in humid tropical regions.

Settlement—Gradual Compression

While embankments and hill slopes may fail abruptly due to stresses that exceed the soil's strength, most foundation problems result from slow, often uneven, vertical subsidence or **settlement** of the soil.

Compaction Control. People attempting to grow plants generally avoid any practice that might compact the soil. However, soils to be used for a foundation or roadbed are compacted on purpose using heavy rollers (Figure 4.60) or vibrators. Compaction occurring after construction would result in uneven settlement and cracked pavements or foundations.

Some soil particles, such as certain silicate clays and micas, can be compressed when a load is placed upon them. If that load is removed, these particles tend to regain their original shape, in effect reversing their compression. As a result, soils rich in these particles are not easily compacted into a stable base for roads and foundations.

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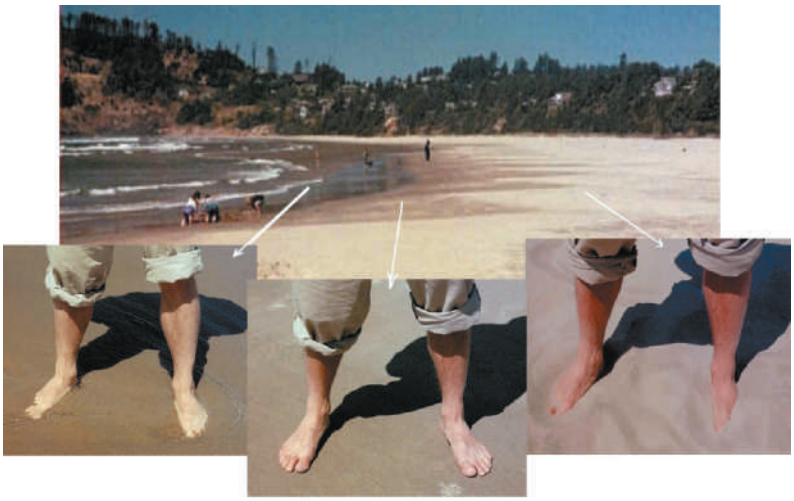

Figure 4.59 *Walk along a beach to learn about soil strength for sandy materials. Your feet easily sink into dry sand as there is nothing to hold the sand particles together. As you move toward the ocean the soil is moistened by incoming waves, but no inundated. Here, thin water films bridge between sand particles, holding them together so they resist penetration. If you stand along the edge of the ocean, once again your feet penetrate the sand, because each particle is completely surrounded by water, which acts more as a lubricant than as a binding force. Soil strength influences soil behaviors from supporting foundations to allowing root penetration.* (Photos courtesy of Ray R. Weil)

The **Proctor test** is used to guide efforts at compacting soil materials before construction. A specimen of soil is mixed to a given water content and placed in a holder, where it is compacted by a drop hammer. The bulk density (usually referred to as the *dry density* by engineers) is then measured. The process is repeated with increasing water contents until a *Proctor curve* (Figure 4.57*b*) can be drawn from the data. The curve indicates the maximum bulk density achievable and the soil water content that maximizes compactability. On construction sites, tanker trucks may spray water to bring the soil water content to the determined optimum level before heavy equipment (such as that shown in Figure 4.60) compacts the soil to the desired density.

Compressibility. A **consolidation test** may be conducted on a soil specimen to determine its **compressibility**—how much its volume will be reduced by a given applied force. Because of the relatively low porosity and equidimensional shape of the individual mineral grains, very sandy soils resist compression once the particles have settled into a tight packing arrangement. They make excellent soils for foundations. The high porosity of clay floccules and the flakelike shape of clay particles give clayey soils much greater compressibility. Soils consisting mainly of organic matter (peats) have the highest compressibilities and generally are unsuitable for foundations.

In the field, compression of wet, clayey soils may occur very slowly after a load (e.g., a building) is applied because compression can occur only as fast as water can escape from the soil pores—which for the fine pores in clayey materials is not very fast. Perhaps the most famous example of uneven settlement due to slow compression is the Leaning Tower of Pisa in Italy. Unfortunately, most cases of uneven settlement result in headaches, not tourist attractions.

Expansive Soils

Some clays, particularly the smectites (see Section 8.3), swell when wet and shrink when dry. Expansive soils are rich in these types of clay. The electrostatic charges on clay surfaces attract water molecules from larger pores into the micropores within clay domains. Also, the adsorbed cations associated with the clay surfaces tend to hydrate, drawing in additional water. The water pushes apart the layers of clay, causing the mass of soil to swell in volume. The reverse of these processes occurs when the soil dries and water is withdrawn from packets of clay platelets, causing shrinkage and cracking. After a prolonged dry spell, soils high in smectites can be recognized in the field by the crisscrossed pattern of wide, deep cracks (Figure 4.61). The swelling and shrinkage cause sufficient movement of the soil to crack building foundations, burst pipelines, and buckle pavements.

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Figure 4.60 *Compaction of soils used as foundations and roadbeds is accomplished by heavy equipment such as this sheepsfoot roller. The knobs ("sheepsfeet") concentrate the mass on a small impact area, punching and kneading the loose, freshly graded soil to optimum density.* (Photo courtesy of Ray R. Weil)

Figure 4.61 *Certain types of clays, especially the smectites, undergo significant volume changes in conjunction with changes in water content. Here, an expansive soil rich in smectitic clay has shrunk during a dry period, causing a network of large cracks to open up in the soil surface.* (Photo courtesy of N. C. Brady)

Construction Hazards of Expansive Soils.[12] Figure 4.62 gives an example of special steps needed to safely build homes on soils dominated by smectitic clay. The cost of building homes on smectitic soils may be double that of building on soils dominated by nonswelling clays, for which conventional foundation designs can be safely used. If preventative design measures are not taken during the construction of houses on smectite clays, homeowners will pay dearly in the future. The building foundation is likely to move with the swelling and shrinking of the soil, misaligning doors and windows and eventually cracking foundations, walls, and pipes. During extended dry periods soils under and around building foundations become unusually dry resulting in major shrinkage even in only moderately expansive soils. Soil shrinkage occurred widely during the great drought of 2012 in the central USA, saddling thousands of surprised homeowners with individual repair bills as high as $100,000.

Damage caused by expansive soils only rarely makes news headlines, although in many industrialized countries the total cost annually exceeds that caused by tornados, floods, or earthquakes. For example, expansive clays occur on about 20% of the land area in the United States and cause upwards of $10 billion in damages annually to pavements, foundations, and utility lines. The damages can be severe in certain sites in all parts of the country, but are most extensive in regions that have long dry periods alternating with periods of rain.

Atterberg Limits

As a dry, clayey soil takes on increasing amounts of water, it undergoes dramatic and distinct changes in behavior and consistency. A hard, rigid solid in the dry state, it becomes a crumbly

[12]For news coverage of homeowner problems with soil shrinkage during severe drought, see Salter (2012).

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Figure 4.62 *The different swelling tendencies of two types of clay are illustrated in the lower left. All four cylinders initially contained dry, sieved clayey B horizon soil, the two on the left are a kaolinitic soil, the two on the right are smectitic. An equal amount of water was added to the two center cylinders. The kaolinitic soil settled a bit and was not able to absorb much of the water. The smectitic soil swelled about 25% in volume and absorbed nearly all the added water. The scenes to the right and above show a practical application of knowledge about these clay properties. Soils containing large quantities of smectite undergo pronounced volume changes as the clay swells and shrinks with wetting and drying. Such soils (e.g., the California vertisol shown here) make very poor building sites. The normal-appearing homes (upper) are actually built on deep, reinforced-concrete pilings (lower right) that rest on nonexpansive substrata. The 15–25 such pilings needed for each home more than doubles the cost of construction.* (Photos courtesy of Ray R. Weil)

(friable) semisolid when a certain moisture content (termed the **shrinkage limit**) is reached. If it contains expansive clays, the soil also begins to swell in volume as this moisture content is exceeded. Increasing the water content beyond the **plastic limit** will transform the soil into a malleable, plastic mass and cause additional swelling. The soil will remain in this plastic state until its **liquid limit** is exceeded, causing it to transform into a viscous liquid that will flow when jarred. These critical water contents (measured in units of percent) are termed the **Atterberg limits**.

Plasticity Index (PI). The PI is the difference between the plastic limit (PL) and liquid limit (LL) and indicates the water-content range over which the soil has plastic properties:

$$PI = LL - PL$$

Soils with a plasticity index greater than about 25 are usually expansive clays that make poor roadbeds (Figure 3.32) or foundations. Figure 4.62 shows the relationship among the Atterberg limits and the changes in soil volume associated with increasing water contents for a hypothetical soil.

Coefficient of Linear Extensibility (COLE). The expansiveness of a soil (and therefore the hazard of its destroying foundations and pavements) can be quantified as the COLE. Figure 4.63 indicates how the volume change used to calculate the COLE relates to the Atterberg limits. Suppose a sample of soil is moistened to its plastic limit and molded into the shape of a bar with length L_M. If the bar of soil is allowed to air dry, it will shrink to length L_D. The COLE is the percent reduction in length of the soil bar upon shrinking:

$$COLE = \frac{L_M - L_D}{L_M} \times 100$$

The COLE and the PI are two measures of soil expansiveness (see Section 4.9). Both are much higher for smectitic soils than kaolinitic ones (Table 4.9). Relatively pure, mined

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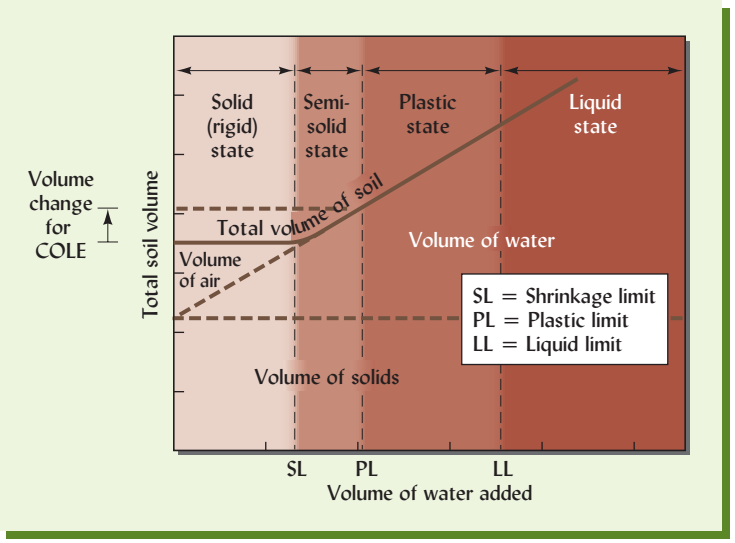

Figure 4.63 *A common depiction of the Atterberg limits, which mark major shifts in the behavior of a cohesive soil as its water content changes (from left to right). As water is added to a certain volume of dry solids, first air is displaced; then, as more water is added, the total volume of the soil increases (if the soil has some expansive properties). When the shrinkage limit (SL) is reached, the once rigid, hard solid becomes a crumbly semisolid. With more water, the plastic limit (PL) is reached, after which the soil becomes plastic and can be molded. It remains in a plastic stage over a range of water contents until the liquid limit (LL) is exceeded, at which point the soil begins to behave as a viscous liquid that will flow when jarred. The volume change for calculating the coefficient of linear extensibility (COLE) is shown at the left.* [Diagram courtesy of Ray R. Weil]

Table 4.9
PLASTIC AND LIQUID LIMITS OF THE CLAYEY B HORIZONS OF SEVERAL SOILS AND PURE SMECTITE CLAY

All soils listed are high in clay, but those dominated by smectite and other high-activity clays tend to have the highest plasticity indices and coefficients of linear extensibility (COLE). Also, note the effect of saturating cation on the liquid limit of pure smectite clay.

Soil	Clay content, %	Clay mineralogy	Plastic limit, %	Liquid limit, %	Plasticity index	COLE[a]
Bashaw (Aquerts)	65	Smectitic	18	71	53	—
Jackland (Udalfs)	68	Smectitic	42	90	48	0.16
Waxpool (Aqualfs)	68	Smectitic	36	76	40	0.18
Kelly (Udalfs)	59	Vermiculitic	12	45	33	0.10
Creedmoor (Udults)	54	Mixed, semiactive	36	67	31	0.09
Cecil (Udults)	68	Kaolinitic	43	61	18	0.03
Davidson (Udults)	68	Kaolinitic	40	56	16	0.04
Slickrock (Udands)	45	Iron oxides	46	59	13	—
Brazil Oxisol (Aquox)	60	Kaolinitic	25	45	20	0.03
Na-saturated smectite	100	—	—	950	—	—
Ca-saturated smectite	100	—	—	360	—	—
Na-saturated kaolinite	100	—	—	36	—	—

[a]Coefficients of linear extensibility, see Section 4.9.
Whole soils data from USDA/NRCS (2005) and McNabb (1979); pure clay data from Warkentin (1961).

smectite clay (often sold as "bentonite"), especially when saturated with Na^+ ions, can have far greater potential for swelling and plasticity than the impure clays in soil. Smectite clays (see Section 8.3) generally have high liquid limits and plasticity indices, especially if saturated with sodium. Kaolinite and other nonexpansive clays have low liquid limit values. The tendency of expansive clay soils to literally flow down steep slopes when the liquid limit is exceeded, producing mass wasting and landslides, is illustrated in Figure 4.58).

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Table 4.10
THE UNIFIED SYSTEM OF CLASSIFICATION USED TO CLASSIFY SOIL MATERIALS (NOT NATURAL SOIL BODIES) FOR ENGINEERING USES[a]

Coarse-grained soils 50% or more retained on No. 200 (0.075 mm) sieve							
Gravels more than 50% of coarse fraction retained on No. 4 (2 mm) sieve				Sands more than 50% of coarse fraction passes No. 4 (2 mm) sieve			
Clean gravels		Gravels with fines		Clean sands		Sands with fines	
GW	GP	GM	GC	SW	SP	SM	SC
Well- graded gravels and gravel- sand mixtures, little to no fines	Poorly-graded gravels and gravel- sand mixtures, little to no fines	Silty gravels and gravel- sand mixtures	Clayey gravels and gravel- sand mixtures	Well- graded sands and gravelly sands, little to no fines	Poorly-graded sands and gravelly sands, little to no fines	Silty sands, sand-silt mixtures	Clayey sands, sand-clay mixtures

Fine-grained soils 50% or more passes No. 200 (0.075 mm) sieve						
Silts and clays Liquid limit 50% or less			Silts and clays Liquid limit greater than 50%			Highly organic soils
ML	CL	OL	MH	CH	OH	Pt
Inorganic silts, very fine sands, rock flour, silty or clayey fine sands	Inorganic clays of low to medium plasticity, gravelly, sandy or, silty clays, lean clays	Organic silts and organic silty clays of low plasticity	Inorganic silts, micaceous or diatomaceous fine sand or silts, elastic silts	Inorganic clays of high plasticity, fat clays	Organic clays of medium to high plasticity	Peat, muck, other highly organic soils

[a]The two-letter designations (SW, MH, etc.) help engineers predict the behavior of the soil material when used for construction purposes. The first letter is one of the following: G = gravel, S = sand, M = silts, C = clays, O = organic-rich materials. The second letter indicates whether the sand or gravels are well graded (W) or poorly graded (P), and whether the silts, clays, and organic-rich materials have a high plasticity index (H) or a low plasticity index (L). Among the fine-grained materials, those closer to the right side of the table are the most troublesome materials for foundations and roadbeds.

Unified Classification System for Soil Materials

The U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation have established a widely used system of classifying soil materials to predicting their behavior in engineering applications (Table 4.10). The system first groups soils into coarse- and fine-grained soils. The coarse materials are further divided on the basis of grain size (gravels and sands), amount of fines present, and uniformity of grain size (well or poorly graded). The fine-grained soils are divided into silts, clays, and organic materials. These classes are further subdivided on the basis of their liquid limit (above or below 50) and their plasticity index. Each type of soil is then given a two-letter designation based primarily on its particle-size distribution (texture), Atterberg limits, and organic matter content (e.g., GW for well-graded gravel, SP for poorly graded sands, CL for clay of low plasticity, and OH for organic-rich clays of high plasticity). This classification of soil materials helps engineers predict the soil strength, expansiveness, compressibility, and other properties so that appropriate engineering designs can be made for the soil at hand (Box 4.7).

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BOX 4.7

TRAGEDY IN THE BIG EASY—A LEVEE DOOMED TO FAIL[a]

After Hurricane Katrina hit New Orleans, USA, in 2005, a 4-m-high storm surge breached the city's levees in several places, causing one of the worst disasters in American history with some 100,000 homes flooded and over 1000 people killed. Some of the greatest flooding occurred when the 17th Street levee failed (Figure 4.64). Investigations later showed that the 17th Street levee was doomed to fail by a faulty levee design that did not properly deal with underlying layers of organic soils and sands. Poor design, combined with poor levee maintenance, allowed water to seep under the levee and weaken the soil at its base.

The levee, essentially a gently sloping mound of compacted clay soils, was covered on the landward side with a thin veneer of topsoil to support a protective grass mantle. Hard armor of rock or concrete (see Section 17.10) was not used in most places. To hold back floodwater and storm surges, engineers had constructed a concrete seawall along the crest of the levee. The seawall was attached to long steel pilings driven deep into the soil of the levee. The pilings were meant to both anchor the seawall and to prevent water from seeping through or under the levee. Out of sight, under the layers of clayey and loamy materials from which the levee was constructed, several layers of peat (buried Histosols) and sand provided for the weak link in the levee design.

Organic soils are highly compressible and have very low bearing and shear strengths. Both peats and sands are also highly permeable and conduct water readily. To perform their intended functions, the steel pilings attached to the seawall had to be long enough to penetrate through the peat/sand layers and into the more cohesive, higher-strength soil below. Unfortunately, the pilings in the 17th Street levee were too short (less than 6 m) and failed to penetrate through the peat layer (Figure 4.65). Whenever storm surges—or even high flows—raised the water level in the canal, seepage would occur through the peat/sand layer under the levee. The seepage water would then rise to saturate the soil at the foot of levee. When saturated, the soil would lose most of its shear strength and resistance to compression. Apparently, the engineers designing the levee had data on the peat layers, but based their design on the *average* soil properties, rather than on the weakest soils present.

On August 21, 2005, with seepage water saturating the soil at the levee base and turning the peat layer into little more than "soup," Katrina's storm surge "snapped the chain" at the weakest link, toppling a 140 m long section of the seawall, pushing both it and the levee some 14 m inland. The storm-churned waters poured through the breach, inundating the city of New Orleans.

Figure 4.64 *A large helicopter attempts emergency repairs to the 17th Street levee breach several days after Hurricane Katrina hit New Orleans and toppled this section of the levee and seawall. Large chunks of the levee can be seen some 14 m inland.* (Photo courtesy of U.S. Army Corps of Engineers)

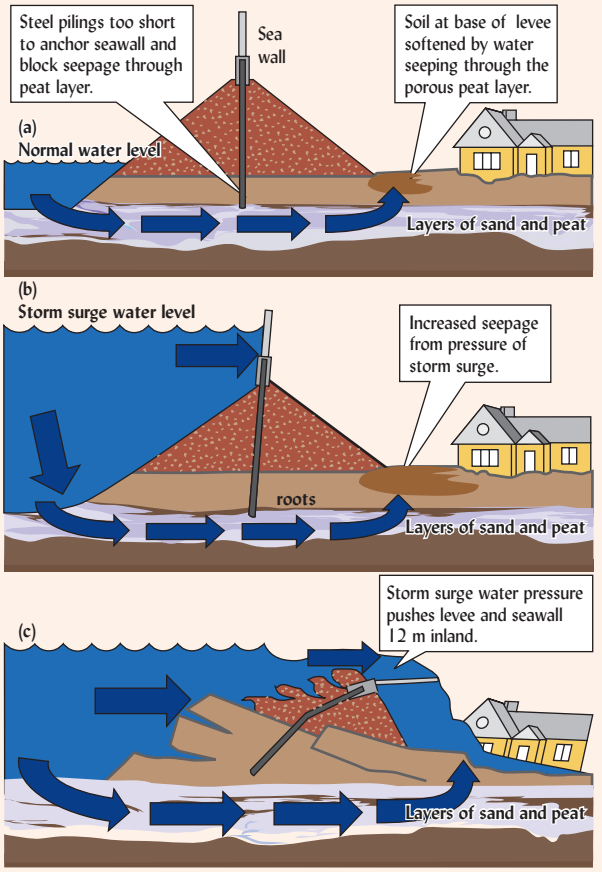

Figure 4.65 *Illustration (not to scale) of how the buried layers of low-strength organic soil (a) allowed seepage of storm surge water (b) dooming the levee and its seawall to failure (c).* (Diagram courtesy of Ray R. Weil)

[a]Based on forensic engineering investigation information in Seed et al. (2005) and reporting by Marshall (2005) and Vartabedian and Braun (2006).

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4.10 CONCLUSION

Soils present an incredibly complex physical network of solid surfaces, pores, and interfaces that provides the setting for a myriad of chemical, biological, and physical processes. These in turn influence plant growth, hydrology, environmental management, and engineering uses of soil. The nature and properties of the individual particles, their size distribution, and their arrangement in soils determine the total volume of nonsolid pore space, as well as the pore sizes, thereby impacting on water and air relationships.

The properties of individual particles and their proportionate distribution (soil texture) are subject to little human control in field soils. However, it is possible to exert some control over the arrangement of these particles into aggregates (soil structure) and on the stability of these aggregates. Tillage and traffic must be carefully controlled to avoid undue damage to soil tilth, especially when soils are rather wet. Generally, nature takes good care of soil structure, and humans can learn much about soil management by studying natural systems. Vigorous and diverse plant growth, generous return of organic residues, and minimal physical disturbance are attributes of natural systems worthy of emulation. Proper plant species selection; crop rotation; and management of chemical, physical, and biological factors can help ensure maintenance of soil physical quality. In recent years, these management goals have been made more practical by the advent of conservation tillage systems that minimize soil manipulations while decreasing soil erosion and water runoff.

Particle size, moisture content, and plasticity of the colloidal fraction all help determine the stability of soil in response to loading forces from traffic, tillage, or building foundations. The physical properties presented in this chapter greatly influence nearly all other soil properties and uses, as discussed throughout this book.

STUDY QUESTIONS

1. If you were investigating a site for a proposed housing development, how could you use soil colors to help predict where problems might be encountered?
2. You are considering the purchase of some farmland in a region with variable soil textures. The soils on one farm are mostly sandy loams and loamy sands, while those on a second farm are mostly clay loams and clays. List the potential advantages and disadvantages of each farm as suggested by the texture of its soils.
3. Revisit your answer to question 2. Explain how soil structure in both the surface and subsurface horizons might modify your opinion of the merits of each farm.
4. Two different timber-harvest methods are being tested on adjacent forest plots with clay loam surface soils. Initially, the bulk density of the surface soil in both plots was 1.1 Mg/m^3. One year after the harvest operations, plot *A* soil had a bulk density of 1.48 Mg/m^3, while that in plot *B* was 1.29 Mg/m^3. Interpret these values with regard to the relative merits of systems *A* and *B*, and the likely effects on the soil's function in the forest ecosystem.
5. What are the textural classes of two soils, the first with 15% clay and 45% silt, and the second with 80% sand and 10% clay? (Hint: Use Figure 4.6.)
6. For the forest plot *B* in question 4, what was the change in percent pore space of the surface soil caused by timber harvest? Would you expect that most of this change was in the micropores or in the macropores? Explain.
7. Discuss the positive and negative impacts of tillage on soil structure. What is another physical consideration that you would have to take into account in deciding whether or not to change from a conventional to a conservation tillage system?
8. What would you, as a home gardener, consider to be the three best and three worst things that you could do with regard to managing the soil structure in your home garden?
9. What does the Proctor test tell an engineer about a soil, and why would this information be important?
10. In a humid region characterized by expansive soils, a homeowner experienced burst water pipes, doors that no longer closed properly, and large vertical cracks in the brick walls. The house had had no problems for over 20 years, and a consulting soil scientist blamed the problems on a large tree that was planted near the house some ten years before the problems began to occur. Explain.

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REFERENCES

Arthur, H. G. 1977. *Teton Dam failure*. The Evaluation of Dam Safety (Engineering Foundation Conference Proceedings. Asilomar). American Society of Civil Engineers, New York, pp. 61–71. http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/narrative.html

Bigham, J. M., and E. J. Ciolkosz (eds.). 1993. *Soil color*. SSSA Special Publication 31. Soil Science Society of America, Madison, WI.

Caesar-TonThat, T., U. Sainju, S. Wright, W. Shelver, R. Kolberg, and M. West. 2011. "Long-term tillage and cropping effects on microbiological properties associated with aggregation in a semi-arid soil." *Biology and Fertility of Soils* **47**:157–165.

Celik, I. 2005. "Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey." *Soil Tillage Research* **83**:270–277.

Chen, G., and R. R. Weil. 2011. "Root growth and yield of maize as affected by soil compaction and cover crops." *Soil and Tillage Research* **117**:17–27.

Di Stefano, C., V. Ferro, and S. Mirabile. 2010. "Comparison between grain-size analyses using laser diffraction and sedimentation methods." *Biosystems Engineering* **106**:205–215.

Emerson, W. W., R. C. Foster, and J. M. Oades. 1986. "Organomineral complexes in relation to soil aggregation and structure." In P. M. Huang and M. Schnitzer (eds.). *Interaction of soil minerals with natural organics and microbes*. SSSA Special Publication 17. Soil Science Society of America, Madison, WI.

Eynard, A., T. E. Schumacher, M. J. Lindstrom, and D. D. Malo. 2004. "Porosity and pore-size distribution in cultivated Ustolls and Usterts." *Soil Science Society of America Journal* **68**:1927–1934.

Faulkner, E. H. 1943. *Plowman's Folly*. University of Oklahoma Press, Norman, OK.

Gent, J. A., Jr., R. Ballard, A. E. Hassan, and D. K. Cassel. 1984. "Impact of harvesting and site preparation on physical properties of Piedmont forest soils," *Soil Science Society of America Journal* **48**:173–177.

Gent, J. A., Jr., and L. A. Morris. 1986. "Soil compaction from harvesting and site preparation in the Upper Gulf Coastal Plain," *Soil Science Society of America Journal* **50**:443–446.

Gilker, R. E., R. R. Weil, D. T. Krizek, and B. Momen. 2002. "Eastern gamagrass root penetration in adverse subsoil conditions." *Soil Science Society America Journal* **66**:931–938.

Halfmann, D. 2005. "Management system effects on water infiltration and soil physical properties." Master's Thesis, Texas Tech University, Lubbock, TX.

Hu, X., L.-Y. Liu, S.-J. Li, Q.-G. Cai, Y.-L. LÃœ, and J.-R. Guo. 2012. "Development of soil crusts under simulated rainfall and crust formation on a loess soil as influenced by polyacrylamide." P*edosphere* **22**:415–424.

Laws, W. D., and D. D. Evans. 1949. "The effects of long-time cultivation on some physical and chemical properties of two rendzina soils," *Soil Science Society of America Proceedings* **14**:15–19.

Lin, H. 2012. "Understanding soil architecture and its functional manifestations across scales." In H. Lin (ed.). *Hydropedolgy: Synergistic integration of soil science and hydrology*. Academic Press, Amsterdam, pp. 41–74.

Lucas, S. T., and R. R. Weil. 2012. "Can a labile carbon test be used to predict crop responses to improve soil organic matter management?" *Agronomy Journal* **104**:1160–1170.

Marshall, B. 2005. "17th Street Canal levee was doomed—report blames Corps: Soil could never hold." *The Times-Picayune*, Wednesday, November 30, New Orleans.

McCarthy, D. F. 1993. *Essentials of soil mechanics and foundations*, 4th ed. Prentice Hall, Englewood Cliffs, NJ.

Parker, M. M., and D. H. Van Lear. 1996. "Soil heterogeneity and root distribution of mature loblolly pine stands in Piedmont soils," *Soil Science Society of America Journal* **60**:1920–1925.

Rillig, M. C., and P. D. Steinberg. 2002. "Glomalin production by an arbuscular mycorrhizal fungus: A mechanism of habitat modification?" *Soil Biology & Biochemistry* **34**:1371–1374.

Ritz, K., and I. Young (eds.) 2011. *Architecture and biology of soils: Life in inner space*. CABI Cambridge, Massachusetts, pp. 1–416.

Ross, C., R. E. Sojka, and J. A. Foerster. 2003. "Scanning electron micrographs of polyacrylamide-treated soil in irrigation furrows." *Journal of Soil and Water Conservation* **58**:327–331.

Salter, J. 2012. "U.S. drought damage: Homes see cracking due to parched soil." Huffington Post, 08/31/12. http://www.huffingtonpost.com/2012/08/31/us-drought-damage-homes_n_1846712.html.

Sasiharan, N. 2003. "The failure of Teton dam – a new theory based on soil mechanics", Washington State University, Pullman, WA.XX.

Seed, R. B., et al. 2005. "Preliminary report on the performance of the New Orleans levee systems in hurricane Katrina on August 29, 2005—Preliminary findings from field investigations and associated studies shortly after the hurricane." Report UCB/CITRIS – 05/01. University of California at Berkeley and the American Society of Civil Engineers, Berkeley, CA.

Singh, P. K. 2012. "Role of glomalin related soil protein produced by arbuscular mycorrhizal fungi: A review." *Agricultural Science Research Journal* **2**:119–125.

Six, J., H. Bossuyt, S. Degryze, and K. Denef. 2004. "A history of research on the link between (micro) aggregates,

FOR REFERENCE PURPOSES ONLY

soil biota, and soil organic matter dynamics." *Soil Tillage Research* 79:7–31.

Six, J., E. T. Elliott, and K. Paustian. 2000. "Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy," *Soil Science Society of America Journal* 64:1042–1049.

Soil Science Society of America. 2001. *Glossary of soil science terms 1996*. Soil Science Society of America, Madison, WI.

Thieme, J., G. Schneider, and C. Knochel. 2003. "X-ray tomography of a microhabitat of bacteria and other soil colloids with sub-100 nm resolution." *Micron* 34:339–344.

Tijink, F. G. J., and J. P. Van Der Linden. 2000. "Engineering approaches to prevent compaction in cropping systems with sugar beet. In R. Horn et al. (eds.). *Subsoil compaction: Distribution, processes and consequences*. Catena Verlag, Reiskirchen, Germany, pp. 442–452.

Tisdall, J. M., and J. M. Oades. 1982. "Organic matter and water-stable aggregates in soils." *Soil Science Society of America Journal* 33:141–163.

USDA-NRCS. 2005. *National soil survey handbook*, title 430-vi. U.S. Department of Agriculture, Natural Resources Conservation Service. http://soils.usda.gov/technical/handbook/ (posted September 2005; verified 23, 2005).

Vartabedian, R., and S. Braun. 2006. "Fatal flaws: Why the walls tumbled in New Orleans." Los Angeles Times, Los Angeles, CA.

Vimmerstadt, J., F. Scoles, J. Brown, and M. Schmittgen. 1982. "Effects of use pattern, cover, soil drainage class, and overwinter changes on rain infiltration on campsites," *Journal of Environmental Quality* 11:25–28.

Watts, C. W., and A. R. Dexter. 1997. "The influence of organic matter in reducing the destabilization of soil by simulated tillage." *Soil Tillage Research* 42:253–275.

Weil, R. R. 2009. *Laboratory manual for introductory soils*, 8th ed. Kendall/Hunt, Dubuque, IO. p. 228.

Weil, R. R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. In F. Magdoff and R. R. Weil (eds.). *Soil organic matter in sustainable agriculture*. CRC Press, Boca Raton, FL, pp. 1–43.

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5 Soil Water: Characteristics and Behavior

Soil conveys and receives water. (Ray R. Weil)

When the earth will … drink up the rain as fast as it falls.
—*H. D. Thoreau*, The Journal

One of nature's simplest chemical compounds, water is a vital component of every living cell. Its unique properties promote a wide variety of physical, chemical, and biological processes. These processes greatly influence almost every aspect of soil development and behavior, from the weathering of minerals to the decomposition of organic matter, from the growth of plants to the pollution of groundwater.

We are all familiar with water. We drink it, wash with it, and swim in it. But water in the soil is something quite different from water in a drinking glass. In the soil, the intimate association between water and soil particles changes the behavior of both. Water causes soil particles to swell and shrink, to adhere to each other, and to form structural aggregates. Water participates in innumerable chemical reactions that release or tie up nutrients, create acidity, and wear down minerals so that their constituent elements eventually contribute to the saltiness of the oceans.

Certain soil water phenomena seem to contradict our intuition about how water ought to behave. Attraction to solid surfaces restricts the free movement of water molecules, making water less liquid and more solidlike in its behavior. In the soil, water can flow up as well as down. Plants may wilt and die in a soil whose profile contains a million kilograms of water in a hectare. A layer of sand or gravel in a soil profile may actually inhibit drainage, rather than enhance it.

Soil–water interactions determine the rates of water loss by leaching, surface runoff, and evapotranspiration, the balance between air and water in soil pores, the rate of change in soil temperature, the rate and kind of metabolism of soil organisms, and the capacity of soil to store and provide water for plant growth.

The characteristics and behavior of water in the soil comprise a common thread that interrelates nearly every chapter in this book. The principles contained in this chapter will help us understand why mudslides occur in water-saturated soils (Chapter 4), why earthworms may improve soil quality (Chapter 11), why wetlands contribute to global ozone depletion (Chapter 13), and why famine stalks humanity in certain regions of the world (Chapter 20). Mastery of the principles presented in this chapter is fundamental to your working knowledge of the soil system.

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5.1 STRUCTURE AND RELATED PROPERTIES OF WATER[1]

The ability of water to influence so many soil processes is determined primarily by the structure of the water molecule. This structure is also responsible for the fact that water is mainly present as a liquid, not as a gas, at temperatures found on Earth. Water is, with the exception of mercury, the *only* inorganic (not carbon-based) liquid found on Earth. Water is a simple compound, its individual molecules containing one oxygen atom and two much smaller hydrogen atoms. The elements are bonded together covalently, each hydrogen atom sharing its single electron with the oxygen.

Polarity

Instead of lining up symmetrically on either side of the oxygen atom (H—O—H), the hydrogen atoms are attached to the oxygen in a V-shaped arrangement at an angle of 105° (Figure 5.1). Consequently, water molecules exhibit *polarity*; that is, the charges are not evenly distributed. Rather, the side on which the hydrogen atoms are located tends to be electropositive and the opposite side electronegative.

Hydrogen Bonding

Through a phenomenon called **hydrogen bonding**, a hydrogen atom of one water molecule is attracted to the oxygen end of a neighboring water molecule, thereby forming a low-energy bond between the two molecules. This type of bonding accounts for the polymerization of water. Hydrogen bonding also accounts for the relatively high boiling point, specific heat, and viscosity of water compared to the same properties of other hydrogen-containing compounds, such as H_2S, which has a higher molecular weight but no hydrogen bonding.

Hydration

Polarity also explains why water molecules are attracted to electrostatically charged ions and to colloidal surfaces. Cations such as H^+, Na^+, K^+, and Ca^{2+} become hydrated through their attraction to the oxygen (negative) end of water molecules. Likewise, negatively charged clay surfaces attract water, this time through the hydrogen (positive) end of the molecule. Polarity of water molecules also encourages the dissolution of salts in water since the ionic components have greater attraction for water molecules than for each other.

When water molecules become attracted to electrostatically charged ions or clay surfaces, they are more closely packed than in pure water. In this packed state, their freedom of movement is restricted and their energy status is lower than in pure water. Thus, when ions or clay particles become hydrated, energy is released. That released energy is evidenced as *heat of solution* when ions hydrate or as *heat of wetting* when clay particles become wet. The latter phenomenon can be demonstrated by adding a few drops of water to dry,

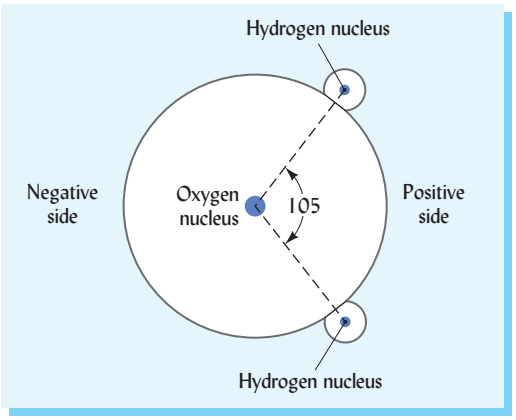

Figure 5.1 *Two-dimensional representation of a water molecule showing a large oxygen atom and two much smaller hydrogen atoms. The H—O—H angle of 105° results in an asymmetrical arrangement. One side of the water molecule (that with the two hydrogens) is electropositive; the other is electronegative. This accounts for the polarity of water.*

[1]For more in-depth discussions of water–soil interactions, see pp. 91–167 in Hillel (2004) or Warrick (2001).

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fine clay. A rise in temperature can be measured—or even felt if the clay is wetted in the palm of one's hand.

Cohesion Versus Adhesion

Hydrogen bonding accounts for two basic forces responsible for water retention and movement in soils: the attraction of water molecules for each other (**cohesion**) and the attraction of water molecules for solid surfaces (**adhesion**). By adhesion (also called *adsorption*), some water molecules are held rigidly at the surfaces of soil solids. In turn, these tightly bound water molecules hold, by cohesion, other water molecules farther removed from the solid surfaces (Figure 5.2). Together, the forces of adhesion and cohesion make it possible for the soil solids to retain water and control its movement and use. Adhesion and cohesion also make possible the property of plasticity possessed by clays (see Section 4.9).

Surface Tension

Another important property of water that markedly influences its behavior in soils is that of **surface tension**. This property is commonly evidenced at liquid–air interfaces and results from the greater attraction of water molecules for each other (cohesion) than for the air above. The net effect is an inward force at the surface that causes water to behave as if its surface were covered with a stretched elastic membrane (Figure 5.3). Because of the relatively high attraction of water molecules for each other, water has a high surface tension (72.8 millinewtons/m at 20 °C) compared to that of most other liquids (e.g., ethyl alcohol, 22.4 mN/m). As we shall see, surface tension contributes to the phenomenon of capillarity, which determines how water moves and is retained in soil.

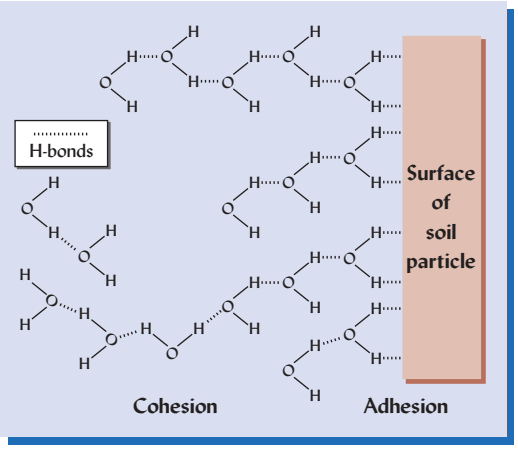

Figure 5.2 *The forces of cohesion (between water molecules) and adhesion (between water and solid surface) in a soil–water system. The forces are largely a result of H-bonding shown as broken lines. The adhesive or adsorptive force diminishes rapidly with distance from the solid surface. The cohesion of one water molecule to another results in water molecules forming temporary clusters that are constantly changing in size and shape as individual water molecules break free or join up with others. The cohesion between water molecules also allows the solid to indirectly restrict the freedom of water for some distance beyond the solid–liquid interface.*

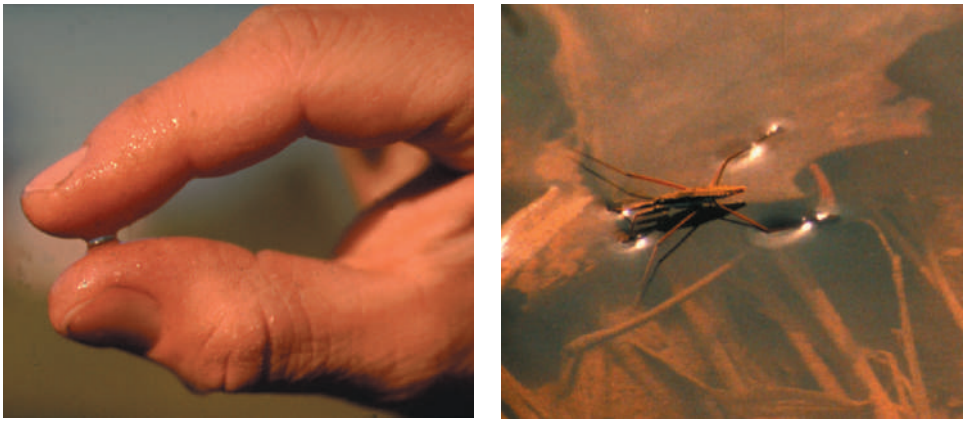

Figure 5.3 *Everyday evidences of the forces of cohesion and adhesion* (left) *as a drop of water is held between the fingers, and of water's surface tension* (right) *as insects walking on water depress the water surface but do not sink.* (Photos courtesy of Ray R. Weil)

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5.2 CAPILLARY FUNDAMENTALS AND SOIL WATER

The movement of water up a wick typifies the phenomenon of capillarity. Two forces cause capillarity: (1) the attraction of water for the solid (adhesion or adsorption), and (2) the surface tension of water, which is due largely to the attraction of water molecules for each other (cohesion).

Capillary Mechanism

Capillarity can be demonstrated by placing one end of a fine (< 1 mm diameter), clean glass tube in water. The water rises in the tube; the smaller the tube bore, the higher the water rises. The water molecules are attracted to the sides of the tube (adhesion) and start to spread out along the glass in response to this attraction. At the same time, the cohesive forces hold the water molecules together and create surface tension, causing a curved surface (called a *meniscus*) to form at the interface between water and air in the tube (Figure 5.4*c*). Lower pressure under the meniscus in the glass tube (P2) allows the higher pressure (P1) on the free water to push water up the tube. The process continues until the water in the tube has risen high enough that its weight just balances the pressure differential across the meniscus (see Box 5.1 for details).

The height of rise in a capillary tube is inversely proportional to the tube radius r. Capillary rise is also inversely proportional to the density of the liquid and is directly proportional to the liquid's surface tension and the degree of its adhesive attraction to the soil surface. If we limit our consideration to water at a given temperature (e.g., 20 °C), then these factors can be combined into a single constant, and we can use a simple capillary equation to calculate the height of rise h:

$$h = \frac{0.15}{r} \tag{5.1}$$

where both h and r are expressed in centimeters. This equation tells us that the smaller the tube bore, the greater the capillary force and the higher the water rise in the tube (Figure 5.5*a*).

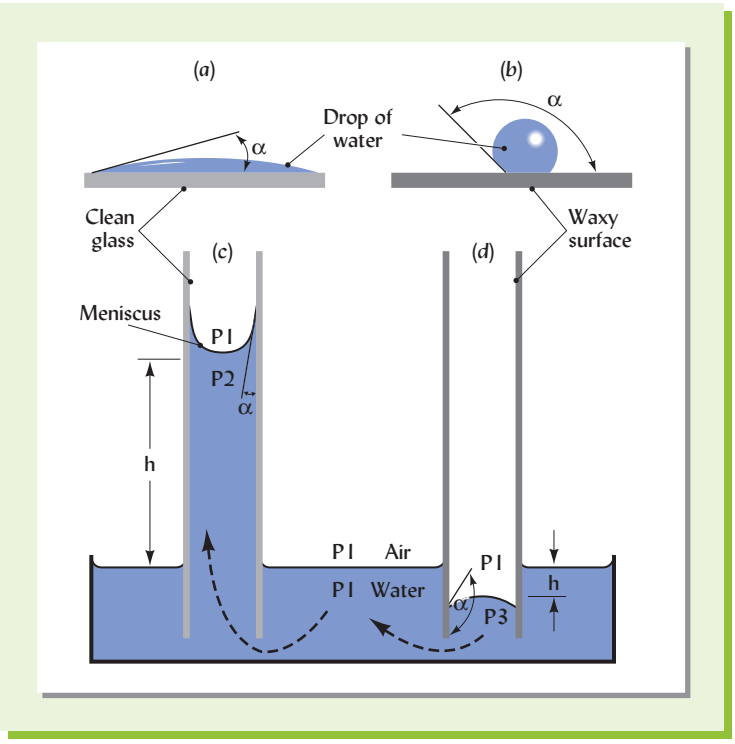

Figure 5.4 *The interaction of water with a hydrophilic* (a, c) *or a hydrophobic* (b, d) *surface results in a characteristic* contact angle (α). *If the solid surface surrounds the water as in a tube, a curved water–air interface termed the* meniscus *forms because of adhesive and cohesive forces. When air and water meet in a curved meniscus, pressure on the convex side of the curve is lower than on the concave side.* (c) *Capillary rise occurs in a fine hydrophilic (e.g., glass) tube because pressure under the* meniscus *(P2) is less than pressure on the free water.* (d) *Capillary depression occurs if the tube is hydrophobic, and the meniscus is inverted.* (Diagram courtesy of Ray R. Weil)

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BOX 5.1

THE MECHANISM OF CAPILLARITY

Capillary action is caused by the combined forces of adhesion and cohesion, as seen when a drop of water is placed on a solid surface. Solid substances that have an electronegative surface (e.g., due to the oxygens in the silica tetrahedra of quartz or glass) strongly attract the electropositive H-end of the water molecule. These substances are said to be *hydrophilic* (water-loving) because attraction of the water molecules for the solid surface (adhesion) is much greater than the attraction of the water molecules for each other (cohesion). Adhesion will cause a drop of water placed on a hydrophilic solid, such as clean glass, to spread out along the surface, thus forming an acute (<90°) angle between the water–air interface and the solid surface (see Figure 5.4*a*). This *contact angle* is characteristic for a particular liquid–solid pair (e.g., water on glass). The more strongly the water molecules are attracted to the solid, the closer to zero the contact angle.

In contrast, water molecules placed on a hydrophobic (water-hating) surface will pull themselves into a spherical mass. The resulting contact angle is obtuse (>90°), indicating that the adhesion is not as strong as the cohesion (see Figure 5.4*b*). This relationship explains why water beads up on a freshly waxed automobile.

Now instead of a flat surface and a drop of water, consider a small-diameter tube of clean glass dipped into a pool of water. Adhesion will again cause the water to spread out on the glass surface, forming the same contact angle α with the glass as was the case for the water drop. At the same time, cohesion among water molecules creates a surface tension that causes a curved surface (called a *meniscus*) to form at the interface between the water and the air in the tube (see Figure 5.4*c*). If the contact angle is nearly zero, the curvature of the meniscus will approximate a hemisphere.

The curved (rather than a flat) interface between water and air causes the pressure to be lower on the convex side (labeled P2 in Figure 5.4*c*) than on the concave side of the meniscus. Normal atmospheric pressure P1 is exerted both above the meniscus and on the pool of free water. Because the pressure under the meniscus P2 is less than the pressure on the free-water pool, water is pushed up the capillary tube. The water will rise in the tube until the meniscus reaches the height *h* at which the weight of the water in the tube just balances the pressure difference P2–P1. In this condition, the forces pushing water up the tube will be balanced by the forces pulling it down.

The upward forces are determined by the product of surface tension *T*, the length of the contact between the tube and the meniscus (tube *circumference* $= 2\pi r$) and the upward component of this force ($\cos \alpha$).

The downward forces are determined by the product of the water density *d*, the water volume above the free-water surface $h\pi r^2$, and the acceleration of gravity *g*.

Thus, when capillary rise ceases we can equate:

$$\text{Upward-acting force} = \text{Downward-acting force}$$

$$T \times 2\pi r \times \cos \alpha = \mathrm{d} \times h \times \pi r^2 \times g \qquad (5.2)$$

Note that if the tube radius were made half as large ($0.5r$), the force acting upward would be cut in half, but the downward force would be 1/4 as great $[(0.5r)^2 = 0.5r * 0.5r = 0.25r]$—hence, the height of rise would be twice as great when the forces come into balance again. Herein lies the reason why capillarity rise is greater in finer tubes. The equation balancing the upward- and downward-acting forces can be algebraically rearranged to give an equation describing the height of capillary rise:

$$h = \frac{2T \cos \alpha}{rdg} \qquad (5.3)$$

Most water–solid interactions in soils are of the hydrophilic type shown in Figure 5.4*a* and *c*. The attraction between water and soil particle surfaces is usually so strong that the angle of contact is very close to zero, making its cosine 1. The $\cos \alpha$ can therefore be ignored under these circumstances. Three of the other factors affecting capillary rise (*T*, *d*, and *g*) are constants at a given temperature and can therefore be combined into a single constant. Thus, we can rewrite the simplified capillary rise equation (eq. 5.01) as:

$$h\,(\mathrm{cm}) = \frac{0.15\,(\mathrm{cm})^2}{r\,(\mathrm{cm})} \qquad (5.4)$$

As one would expect, capillary rise will only occur if the tube is made of hydrophilic material. If a *hydrophobic* tube (such as one with a waxed surface) is dipped into a pool of water, the meniscus will be convex rather than concave to the air, so that the situation is reversed and capillary *depression* rather than capillary *rise* will occur (see Figure 5.4*d*). This is the case in certain water-repellent soil layers (see Figures 5.6 and 7.33).

Height of Rise in Soils

Capillary forces are at work in all moist soils. However, the rate of movement and the rise in height are less than one would expect on the basis of soil pore size alone. One reason is that soil pores are not straight, uniform openings like glass tubes. Furthermore, some soil pores are filled with air, which may be entrapped, slowing down or preventing the movement of water by capillarity (see Figure 5.5*b*).

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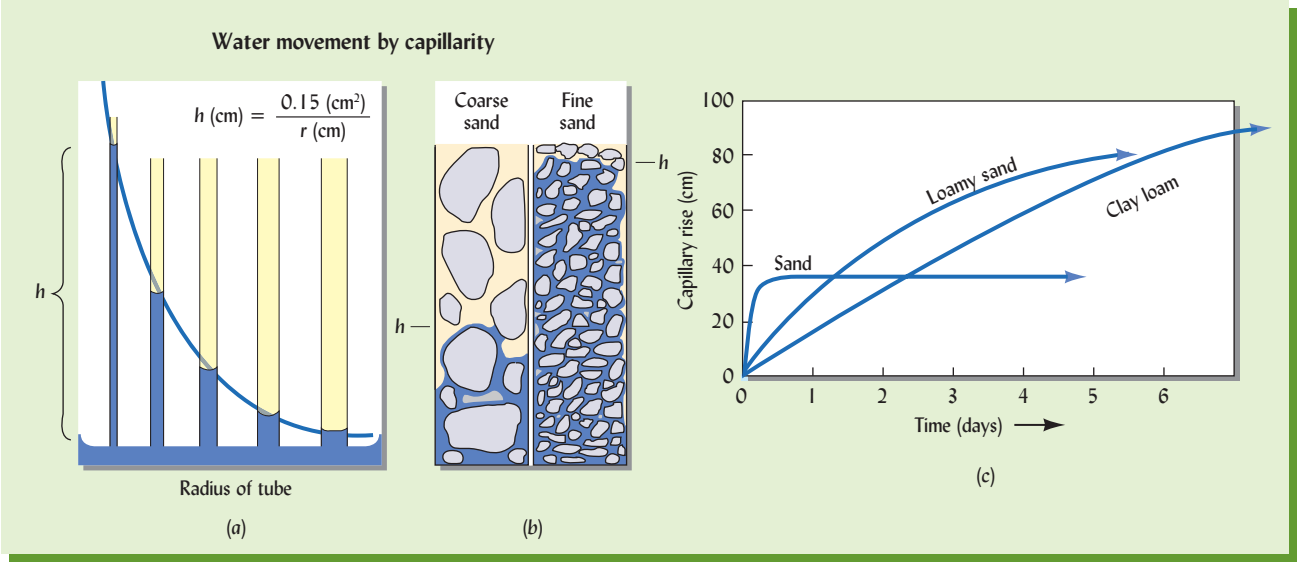

Figure 5.5 *Upward capillary movement of water through tubes of different bore and soils with different pore sizes.* (a) *The capillary equation can be graphed to show that the height of rise* h *doubles when the tube inside radius is halved. The same relationship can be demonstrated using glass tubes of different bore size.* (b) *The same principle also relates pore sizes in a soil and height of capillary rise, but the rise of water in a soil is rather jerky and irregular because of the tortuous shape and variability in size of the soil pores (as well as because of pockets of trapped air).* (c) *The finer the soil texture, the greater the proportion of small-sized pores and, hence, the higher the ultimate rise of water above a free-water table. However, because of the much greater frictional forces in the smaller pores, the capillary rise is much slower in the finer-textured soil than in the sand.* (Diagrams courtesy of Ray R. Weil)

Since capillary movement is determined by pore size, it is the pore-size distribution discussed in Chapter 4 that largely determines the amount and rate of movement of capillary water in the soil. The abundance of medium- to large-sized capillary pores in sandy soils permits rapid initial capillary rise, but limits the ultimate height of rise[2] (Figure 5.5*c*). Clays have a high proportion of very fine capillary pores, but frictional forces slow down the rate at which water moves through them. Consequently, in clays the capillary rise is slow initially, but in time it generally exceeds that of sands. Loams exhibit capillary properties between those of sands and clays.

Capillarity is traditionally illustrated as an upward adjustment. But movement in any direction takes place, since the attractions between soil pores and water are as effective in forming a water meniscus in horizontal pores as in vertical ones (Figure 5.6). The significance of capillarity in controlling water movement in small pores will become evident as we turn to soil water energy concepts.

5.3 SOIL WATER ENERGY CONCEPTS

The retention and movement of water in soils, its uptake and translocation in plants, and its loss to the atmosphere are all energy-related phenomena. *Kinetic energy* is certainly an important factor in the rapid, turbulent flow of water in a river, but the movement of water in soil is so slow that the kinetic energy component is usually negligible. *Potential energy* is most important in determining the status and movement of soil water. For the sake of simplicity, in our discussion of soil water, we will use the term *energy* to refer to potential energy.

[2]Note that if water rises by capillarity to a height of 37 cm above a free-water surface in a sand (as shown in the example in Figure 5.5*c*), then it can be estimated (by rearranging the capillary equation to $r = 0.15/h$) that the smallest continuous pores must have a radius of about 0.004 cm (0.15/37 = 0.004). This calculation gives an approximation of the minimum effective capillary pore radius in a soil.

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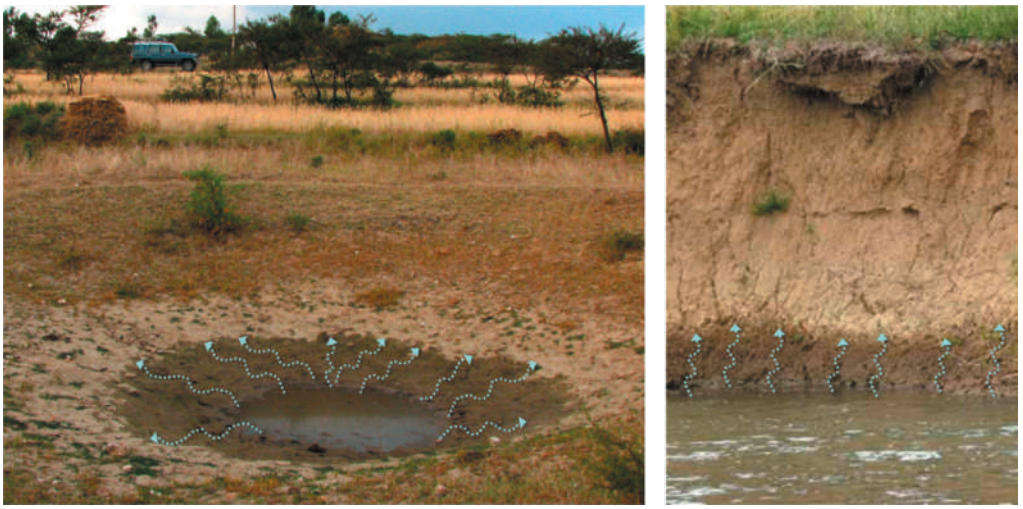

Figure 5.6 *Capillary water movement in the field can be both vertical and horizontal.* (Left) *Capillary flow has caused water in a small surface runoff collection basin to move both up and horizontally away from the pool of collected water.* (Right) *Capillary rise above the water level in a stream bank.* (Photos courtesy of Ray R. Weil)

Every day we can see that things tend toward a lower energy state (and that it takes an input of energy—work—to prevent them from doing so). Use your cell phone and its battery runs down from a fully charged high potential energy state to a discharged, low energy state. If you should drop your phone, it would fall from its state of relatively high potential energy in your hand to a lower potential energy state on the floor (where it is closer to the source of gravitational pull). The difference in energy levels (that is how high off the floor you are holding the phone) determines how forcefully transition will occur. In this respect, soil water is no different—it tends to move or from a higher to a lower energy state. Therefore, if we know the pertinent energy levels at various points in a soil, we can predict the direction of water movement. It is the *differences* in energy levels from one contiguous site to another that influence this water movement.

Forces Affecting Potential Energy

The discussion of the structure and properties of water in the previous section suggests three important forces affecting the energy level of soil water. First, adhesion, or the attraction of water to the soil solids (matrix), provides a **matric** force (responsible for adsorption and capillarity) that markedly reduces the energy state of water near particle surfaces. Second, the attraction of water to ions and other solutes, resulting in **osmotic** forces, tends to reduce the energy state of water in the soil solution. Osmotic movement of pure water across a semipermeable membrane into a solution (osmosis) is evidence of the lower energy state of water in the solution. The third major force acting on soil water is **gravity**, which always pulls the water downward. The energy level of soil water at a given elevation in the profile is thus higher than that of water at some lower elevation. This difference in energy level causes water to flow downward.

Soil Water Potential

The *difference* in energy level of water from one site or one condition to another (e.g., between wet soil and dry soil) determines the direction and rate of water movement in soils and in plants. In a wet soil, most of the water is retained in thick water films around particles or in large pores. Therefore, most of the water molecules in a wet soil are not very close to a particle surface and so are not held very tightly by the soil solids (the matrix). In this condition, the water molecules have considerable freedom of movement, so their energy level is near that of water molecules in a pool of pure water outside the soil. In a drier soil, however, the water that remains is located in thin water films, in small pores, and pore

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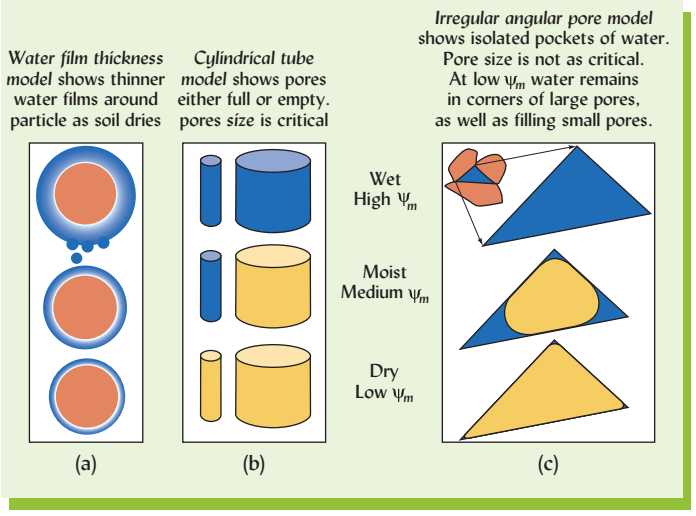

Figure 5.7 *Three models of water distribution in wet, moist or nearly dry soils.* (a) *Water films around soil particles are thicker when the soil is wetter.* (b) *Water is held in soil pores of varying size, the wetter the soil, the larger the pores that are filled with water. As the soil dries, the larger pores are emptied first, leaving water in smaller pores where it is held more tightly.* (c) *Many soil pores are angular with corners in which capillary forces can hold water, even when most of the pore is emptied of water. As the soil dries, the water in the middle of large angular pores is removed first as it is least tightly held by mineral surfaces. Decreasing amounts of water are held in the corners as drying continues. In most soils all three models operate simultaneously and why matric water potential changes as soil water content changes.*
Diagrams courtesy of Ray R. Weil)

corners (Figure 5.7). Thus, the water molecules in a drier soil are close to solid surfaces where they are held tightly and have little freedom of movement. Their energy level is much lower than that of the average water molecules in wet soil. If wet and dry soil samples are brought in touch with each other, water will move from the wet soil (higher energy state) to the drier soil (lower energy).

Relative values of soil water energy can be used to predict how water will move in soils and in the environment. Usually the energy status of soil water in a particular location in the profile is compared to that of pure water at standard pressure and temperature, unaffected by the soil and located at some reference elevation. The *difference* in energy levels between this pure water in the reference state and that of the soil water is termed soil **water potential** (Figure 5.8), the term *potential*, like the term *pressure*, implying a difference in energy status.

If all water potential values under consideration have a common reference point (the energy state of pure water), differences in the water potential of two soil samples in fact reflect differences in their absolute energy levels. This means that water will move from a soil zone having a high soil water potential to one having a lower soil water potential. This fact should always be kept in mind when thinking about the behavior of water in soils.

Several forces are implicated in soil water potential, each of which is a component of the **total soil water potential** ψ_t. These components are due to differences in energy levels resulting from gravitational, matric, submerged hydrostatic, and osmotic forces and are termed **gravitational potential** ψ_g, **matric potential** ψ_m, **hydrostatic potential** ψ_h, and **osmotic potential** ψ_o, respectively. All of these components act simultaneously to influence water behavior in soils. The general relationship of soil water potential to potential energy levels is shown in Figure 5.8 and can be expressed as:

$$\psi_t = \psi_g + \psi_m + \psi_o + \psi_h + \cdots \tag{5.5}$$

where the ellipsis (…) indicates the possible contribution of additional potentials not yet mentioned.

Gravitational Potential

The force of gravity acts on soil water the same as it does on any other body (Figure 5.9), the attraction being toward the Earth's center. The gravitational potential ψ_g of soil water may be expressed mathematically as:

$$\psi_g = gh \tag{5.6}$$

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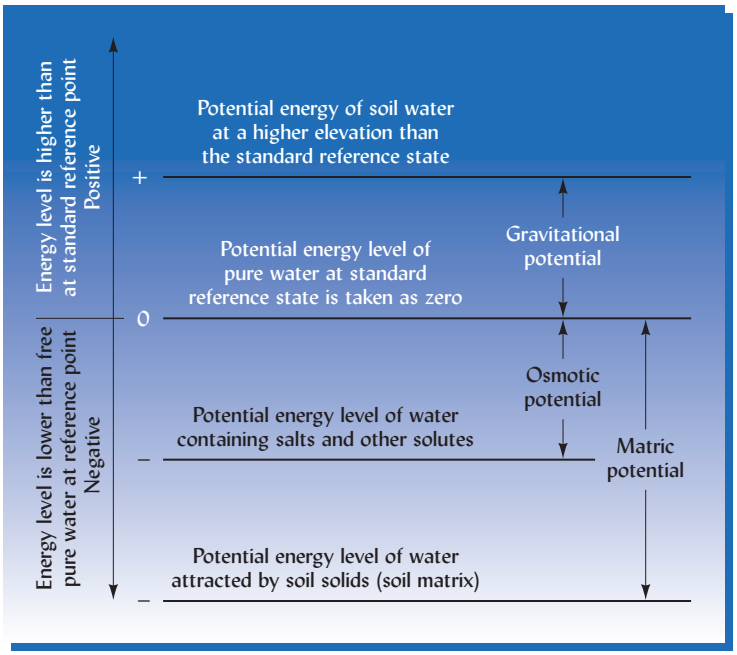

Figure 5.8 *Relationship between the potential energy of pure water at a standard reference state (pressure, temperature, and elevation) and that of soil water. If the soil water contains salts and other solutes, the mutual attraction between water molecules and these chemicals reduces the potential energy of the water, the degree of the reduction being termed* osmotic potential. *Similarly, the mutual attraction between soil solids (soil matrix) and soil water molecules also reduces the water's potential energy. In this case the reduction is called* matric potential. *Since both of these interactions reduce the water's potential energy level compared to that of pure water, the changes in energy level (osmotic potential and matric potential) are both considered to be negative. In contrast, differences in energy due to gravity* (gravitational potential) *are always positive because the reference elevation of the pure water is purposely designated at a site in the soil profile below that of the soil water. A plant root attempting to remove water from a moist soil would have to overcome all three forces simultaneously.* (Diagram courtesy of N. C. Brady)

Figure 5.9 *Whether concerning matric potential, osmotic potential, or gravitational potential (as shown here), water always moves to where its energy state will be lower. In this case the energy lost by the water is used to turn the waterwheel and grind flour at historic Mabry Mills in Virginia, USA.* (Photo courtesy of Ray R. Weil)

where g is the acceleration due to gravity and h is the height of the soil water above a reference elevation. The reference elevation is usually chosen within the soil profile or at its lower boundary to ensure that the gravitational potential of soil water above the reference point will always be positive.

Following heavy precipitation or irrigation, gravity plays an important role in removing excess water from the upper horizons and in recharging groundwater below the soil profile. It will be given further attention when the movement of soil water is discussed (see Section 5.5).

Pressure Potential (Including Hydrostatic and Matric Potentials)

This component accounts for effects on soil water potential other than gravity and solute levels. Pressure potential most commonly includes: (1) the positive hydrostatic pressure due to

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the weight of overlying water in saturated soils and aquifers, and (2) the negative pressure due to the attractive forces between the water and the soil solids or the soil matrix.[3]

The hydrostatic pressures give rise to what is often termed the **hydrostatic potential** ψ_h, a component that is operational only for water in saturated zones below the water table. Anyone who has dived to the bottom of a swimming pool has felt hydrostatic pressure on his or her eardrums.

The attraction of water to solid surfaces gives rise to the **matric potential** ψ_m, which is always negative because the water attracted by the soil matrix has an energy state lower than that of pure water. (These negative pressures are sometimes referred to as *suction* or *tension*. If these terms are used, their values are positive.) The matric potential is operational in unsaturated soil above the water table (Figure 5.10).

Matric potential ψ_m, which results from adhesive forces and capillarity, influences both the retention and movement of soil water. Differences between the ψ_m of two adjoining soil zones encourage the movement of water from wetter (high energy state) areas to drier (low energy state) areas or from large pores to small pores. Although this movement may be slow, it is extremely important in supplying water to plant roots and in engineering applications.

Osmotic Potential[4]

The osmotic potential ψ_o is attributable to the presence of both inorganic and organic substances dissolved in water. As water molecules cluster around solute ions or molecules, the freedom of movement (and therefore the potential energy) of the water is reduced. The greater the concentration of solutes, the more osmotic potential is lowered. As always, water will tend to move to where its energy level will be lower, in this case to the zone of higher solute concentration. However, liquid water will move in response to differences in osmotic potential (the process termed **osmosis**) only if a *semipermeable membrane* exists between the zones of high and low osmotic potential, allowing water through but *preventing the movement of the solute*. If no membrane is present, the solute, rather than the water, generally moves to equalize concentrations. The process of osmosis and the relationship between the matric and osmotic components of total soil water potential is shown in Figure 5.11.

Because soil zones are *not* generally separated by membranes, the osmotic potential ψ_o has little effect on the mass movement of water in soils. Its major effect is on the uptake of

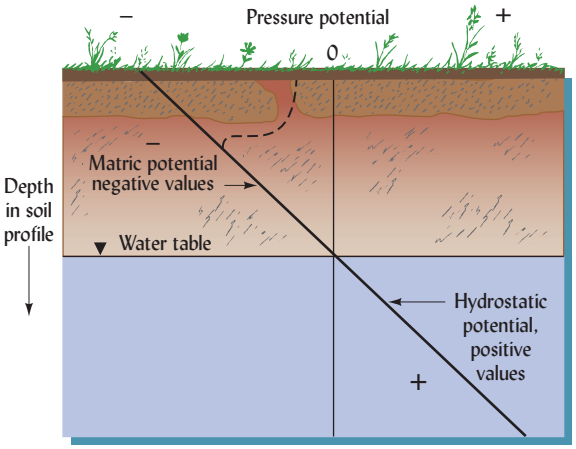

Figure 5.10 *The matric potential and hydrostatic potential are both pressure potentials that may contribute to total water potential. The matric potential is always negative and the hydrostatic potential is positive. The top of the saturated zone is termed the water table. Above the water table, the soil is unsaturated and its water subject to the influence of matric potentials. Water below the water table in saturated soil is subject to hydrostatic potentials. In the example shown, the matric potential decreases linearly with elevation above the water table, signifying that water rising by capillary attraction up from the water table is the only source of water in this profile. Rainfall or irrigation (see dotted line) would alter or curve the straight line, but would not change the fundamental relationship described.*
(Diagram courtesy of Ray R. Weil)

[3]In addition to matric and hydrostatic forces, in some situations the weight of the overburdened soil and the pressure of air in the soil also make a contribution to the total soil water potential.
[4]For a discussion of how osmotic potential govern drought tolerance of plants in global ecosystems, see Bartlett et al. (2012).

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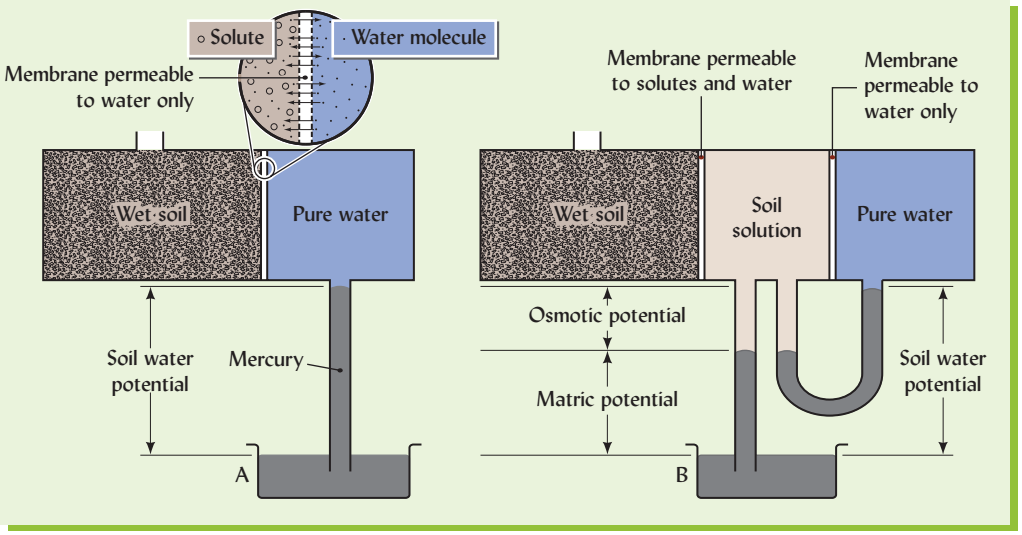

Figure 5.11 *Relationships among osmotic, matric, and combined soil water potentials.* (Left) *A container of soil separated from pure water by a membrane permeable only to water (see inset showing osmosis across the membrane). The pure water is connected to a vessel of mercury through a tube (making a mercury manometer—an instrument for measuring pressures). Water will move into the soil in response to the matric forces attracting water to soil solids and the osmotic forces attracting water to solutes. At equilibrium the height of the mercury column above vessel A is a measure of this combined soil water potential (matric plus osmotic).* (Right) *A second container is placed between the pure water and the soil, and this container is separated from the soil by a fine screen permeable to both solutes and water. Ions will move from the soil into this second container until the concentration of solutes in this water and in the soil water have equalized. Then the difference between the potential energies of this solution and of the pure water gives a measure of the* osmotic potential. *The* matric potential, *as measured by the column of mercury above vessel B, would then be the difference between the combined soil water potential and the osmotic component. The* gravitational potential *(not shown) is the same for all compartments and does not affect the outcome since the water movement is horizontal.* [Based on concepts in Richards (1965)]

water by plant root cells that *are* isolated from the soil solution by their semipermeable cell membranes. In soils high in soluble salts, ψ_o may be lower (have a greater negative value) in the soil solution than in plant root cells. This leads to constraints in the uptake of water by plants. In very salty soil, the soil water osmotic potential may be lower than the plant cytoplasm osmotic potential, thus causing cells in the plant roots to collapse (plasmolyze) as water moves out of the cells to the lower osmotic potential zone in the soil. The drought tolerance of a plant is largely related to its ability to maintain high salt levels in its cells, and thus maintain turgor in leaves even in the face of such low soil water potentials.

The random movement of water molecules causes a few of them to escape a body of liquid water, enter the atmosphere, and become water vapor. Since the presence of solutes restricts the movement of water molecules, fewer water molecules escape into the air as the solute concentration of liquid water is increased. Therefore, water vapor pressure is lower in the air over salty water than in the air over pure water. By affecting water vapor pressure, ψ_o affects the movement of water vapor in soils (see Section 5.7).

Units Used to Quantify Water Potentials

Several units can be used to express differences in energy levels of soil water. One is the *height of a water column* (usually in centimeters) whose weight just equals the potential under consideration. We have already encountered this means of expression since the h in the capillary equation (Section 5.2) tells us the matric potential of the water in a capillary pore. A second unit is the standard *atmosphere* pressure at sea level, which is 760 mm Hg or 1020 cm of water. Another unit termed *bar* approximates the pressure of a standard atmosphere. Energy may be expressed per unit of mass (**joules/kg**) or per unit of volume (**newtons/m**^{2}). In the International System of Units (SI), 1 pascal (Pa) equals 1 newton (N) acting over an area of 1 m^2. In

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Table 5.1
EXPRESSIONS OF SOIL WATER POTENTIAL AND EQUIVALENT DIAMETER OF PORES EMPTIED

Height of unit column of water, cm	Soil water potential, bars	Soil water potential,[a] kPa	Equivalent diameter of pores emptied,[b] μm
0	0	0	—
10.2	−0.01	−1	300
102	−0.1	−10	30
306	−0.3	−30	10
1,020	−1.0	−100	3
15,300	−15	−1,500	0.2
31,700	−31	−3,100	0.097
102,000	−100	−10,000	0.03

[a]The SI unit kilopascal (kPa) is equivalent to 0.01 bars.
[b]Smallest pore that can be emptied by equivalent tension as calculated using Eq. (5.4).

this text we will use Pa or kilopascals (kPa) to express soil water potential. Since other publications may use other units, Table 5.1 is provided to show the equivalency among common means of expressing soil water potential.

5.4 SOIL WATER CONTENT AND SOIL WATER POTENTIAL

The previous discussions suggest an inverse relationship between the water content of soils and the tenacity with which the water is held in soils. Many factors affect the relationship between soil water potential ψ and moisture content θ. A few examples will illustrate this point.

Soil Water Versus Energy Curves

The relationship between soil water potential ψ and moisture content θ of three soils of different textures is shown in Figure 5.12. Such curves are sometimes termed *water release characteristic curves*, or simply *water characteristic curves*. The absence of sharp breaks in the curves indicates a continuous range of pore sizes and therefore a gradual change in the water potential with increased soil water content. The clay soil holds much more water at a given potential than does the loam or sand. Likewise, at a given moisture content, the water is held much more tenaciously in the clay than in the other two soils (note that soil water potential is plotted on a log scale). The amount of clay in a soil largely determines the proportion of very small micropores in that soil. As we shall see, about half of the water held by clay soils is held so tightly in these micropores that it cannot be removed by growing plants. Soil texture clearly exerts a major influence on soil moisture retention.

Soil structure also influences soil water content–energy relationships. A well-granulated soil has more total pore space and greater overall water-holding capacity than one with poor granulation or one that has been compacted. Soil aggregation especially increases the relatively large interaggregate pores (Section 4.5) in which water is held with little tenacity. In contrast, a compacted soil will hold less total water but is likely to have a higher proportion of small- and medium-sized pores that hold water with greater tenacity than do larger pores. Therefore, soil structure predominantly influences the shape of the water characteristic curve in the portion where the potentials are between 0 and about 100 kPa. The shape of the remainder of the curve generally reflects the influence of soil texture.

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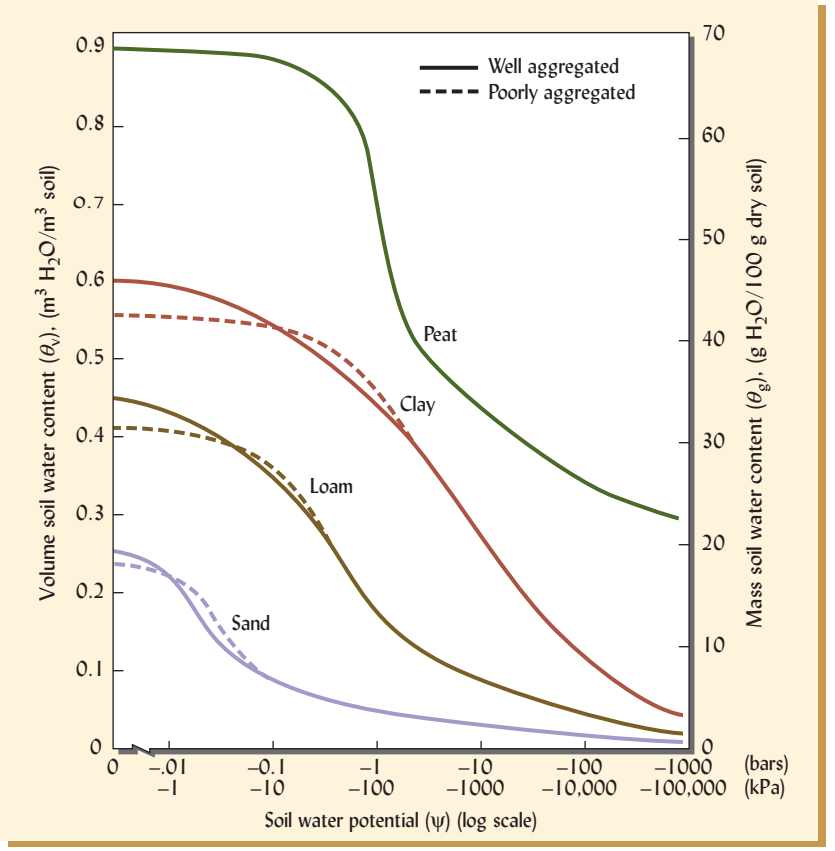

Figure 5.12 *Soil water potential curves for three representative mineral soils and an organic peat. The curves show the relationship obtained by slowly drying completely saturated soils. The dashed lines show the effect of compaction or poor aggregation in mineral soils. Note that the soil water potential ψ (which is negative) is plotted on a log scale in units of bars* (upper scale) *and kilopascals (kPa)* (lower scale). *Soil water content is plotted on the vertical scale on a volumetric basis (left axis). The curves do not account for possible soil volume changes (shrinkage) and are generally representative of data in Rawls et al. (1982, 2004) and Schwärzel et al. (2002).*

The soil water characteristic curves in Figure 5.12 have great practical significance for various field measurements and processes. It will be useful to refer back to these curves as we consider the applied aspects of soil water behavior in the following sections.

Hysteresis

The relationship between soil water content and potential, determined as a soil dries out, will differ somewhat from the relationship measured as the same soil is rewetted. This phenomena, known as **hysteresis**, is illustrated in Figure 5.13. Hysteresis is caused by a number of factors, including the nonuniformity of soil pores. As soils are wetted, some of the smaller pores are bypassed, leaving entrapped air that prevents water penetration. Some of the macropores in a soil may be surrounded only by micropores, creating a bottleneck effect. In this case, the macropore will not lose its water until the matric potential is low enough to empty the water from the surrounding smaller pores (see Figure 5.13). Also, the swelling and shrinking of clays as the soil is dried and rewetted brings about changes in soil structure that affect the soil–water relationships. Because of hysteresis, it is important to know whether soils are being wetted or dried when properties of one soil are compared with those of another.

Measurement of Soil Water Status

The soil water characteristic curves just discussed highlight the importance of making two general kinds of soil water measurements: the *amount* of water present (water content) and the *energy status* of the water (soil water potential). In order to understand or manage water supply and movement in soils, it is essential to have information (directly measured or inferred) on *both* types of measurements. For example, a soil water potential measurement might tell us whether water will move toward the groundwater, but without a corresponding measurement

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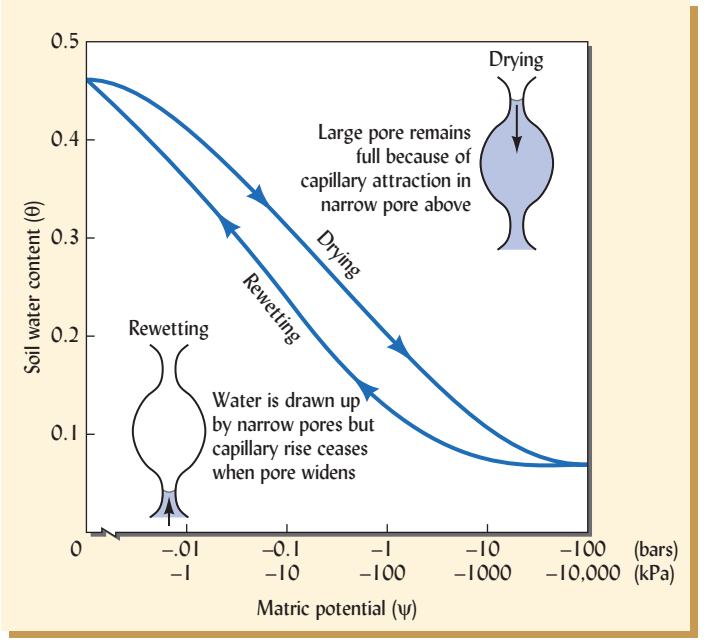

Figure 5.13 *The relationship between soil water content and matric potential of a soil upon being dried and then rewetted. The phenomenon, known as hysteresis, is apparently due to factors such as the nonuniformity of soil pores, entrapped air, and swelling and shrinking. The drawings show the effect of nonuniformity of pores, with large pores at a given water potential (about −33 kPa in the example), either full or empty of water depending on whether the soil is drying or wetting.* (Diagram courtesy of N Brady and Ray R. Weil)

of the soil water content, we would not know the possible significance of the contribution to groundwater.

Generally, the behavior of soil water is most closely related to the energy status of the water, not to the amount of water in a soil. Thus, a clay loam and a loamy sand will both feel moist and will easily supply water to plants when the ψ_m is, say, −10 kPa. However, the amount of water held by the clay loam, and thus the length of time it could supply water to plants, would be far greater at this potential than would be the case for the loamy sand (Figure 5.14).

We will briefly consider several methods for making each of these two types of soil water measurements. Researchers, land managers, and engineers may use a combination of several of these methods to study the storage and movement of water in soil, manage irrigation systems, and predict the physical behavior of soils.

Volumetric Water Content

The **volumetric water content** θ_v is defined as the volume of water associated with a given volume (usually 1 m^3) of dry soil (see Figure 5.12). A comparable expression is the **mass water content** θ_m, or the mass of water associated with a given mass (usually 1 kg) of dry

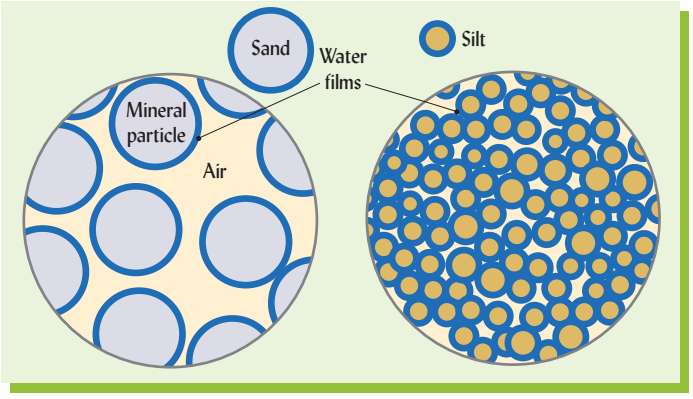

Figure 5.14 *Fine- and coarse-textured soils at the same water potential but very different water contents.* (Left) *Sandy soil at -10 kPa potential in which particles are surrounded by water films of a uniform thickness. Most of the pore space is filled with air.* (Right) *Silty soil at -10 kPa potential with much smaller particle surrounded by uniform films of water of the same thickness as those in the sandy soil. However, the particles and pores are more numerous and smaller than in the sandy soil, so water films of the same thickness cause most of the porespace in the silty soil to be filled with water, not air. Because both soils have the same water potential they would feel similarly moist and could easily supply water to plants, but it is visually obvious that the silty soil has a much greater water content than the sandy soil.* (Diagram courtesy of Ray R. Weil)

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soil. Both of these expressions have advantages for different uses. In most cases we shall use the volumetric water content θ_v in this text.

As compaction reduces total porosity, it also increases θ_v (assuming a given θ_m), therefore often leaving too little air-filled pore space for optimal root activity. However, if a soil is initially very loose and highly aggregated (such as the forested A horizons described in Figure 5.15), moderate compaction may actually benefit plant growth by increasing the volume of pores that hold water between 10 and 1500 kPa of tension (water that plants can utilize).

We think of plant root systems as exploring a certain depth of soil. We measure precipitation (and sometimes irrigation) as a depth of water (e.g., mm of rain). Therefore it is often necessary to express the volumetric water content as a depth of water per unit depth of soil. Conveniently, the numerical values for these two expressions are the same. For example, for a soil containing 0.1 m^3 of water per m^3 of soil (10% by volume) the depth ratio of water is 0.1 m of water per m of soil depth (see also Section 5.9).[5]

Measuring Water Content

Gravimetric Method. The gravimetric method is a direct measurement of soil water content and is therefore the standard method by which all indirect methods are calibrated. The water associated with a given mass (and, if the bulk density of the soil is known, a given volume) of dry soil solids is determined. A sample of moist soil is weighed and then dried at 105 °C for about 24 hours,[6] and finally weighed again. The weight loss represents the soil water. Box 5.2 provides examples of how θ_v and θ_m can be calculated. The gravimetric method is a *destructive* method (a soil sample must be collected for each measurement) and cannot be automated, thereby making it poorly suited to monitoring temporal changes in soil moisture. Several indirect methods of measuring soil water content are nondestructive, easily automated, and very useful in the field (see Table 5.2).

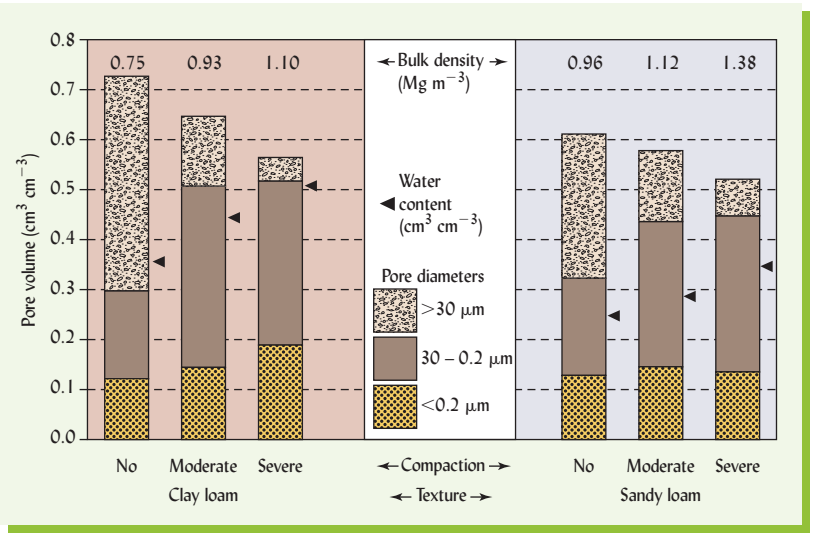

Figure 5.15 *Effect of compaction on volumetric water content θ_v for soils with a given mass water content. Compaction of two forest soils decreased total porosity mainly by converting the largest (usually air-filled) pores into smaller pores that hold water more tightly. These forested A horizon soils were initially so loose that the moderate compaction benefited plants by increasing the volume of water-holding 0.2–30 μm pores. On the other hand, the water originally in the uncompacted soil takes up a greater proportion of the pore volume (indicated as ◀ cm water/cm soil) when the soil is compacted, possibly leading to nearly water-saturated conditions. For example, here the clay loam with severe compaction contains 0.52 cm^3 water, but only 0.04 cm^3 air per cm^3 soil, less than the 0.10 cm^3 air per cm^3 soil (≈ 10% air porosity; see Section 7.2) thought to be required for good plant growth. This figure is worth careful study to understand the relationships among mass and volume water contents, bulk density and porosity.* [Adapted from Shestak and Busse (2005) with permission of The Soil Science Society of America]

[5]When measuring amounts of water added to soil by irrigation, it is customary to use units of volume such as m^3 and hectare-meter (the volume of water that would cover a hectare of land to a depth of 1 m).

[6]Enough drying time must be allowed so that the soil has stopped losing water and has reached a constant weight. To save time, a microwave oven may be used. A dozen small samples of soil (about 20 g each) in glass beakers may be dried on a turntable in a 1000 W microwave oven using three or more consecutive 3 minute periods, stirring the soil between irradiation periods, until the weights no longer decrease.

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BOX 5.2

GRAVIMETRIC DETERMINATION OF SOIL WATER CONTENT

The gravimetric procedures for determining mass soil water content θ_m are relatively simple. Assume that you want to determine the water content of a 100 g sample of moist soil. You dry the sample in a convection oven kept at 105 °C and then weigh it again. Assume that the dried soil now weighs 70 g, which indicates that 30 g of water has been removed from the moist soil. Expressed in kilograms, this is 30 kg water associated with 70 kg dry soil.

Since the mass soil water content θ_m is commonly expressed in terms of kg water associated with 1 kg *dry* soil (*not* 1 kg of *wet* soil!), it can be calculated as follows:

$$\frac{30 \text{ kg water}}{70 \text{ kg dry soil}} = \frac{X \text{ kg water}}{1 \text{ kg dry soil}}$$

$$X = \frac{30}{70} = 0.428 \text{ kg water/kg dry soil} = \theta_m$$

To calculate the volume soil water content θ_v, we need to know the bulk density of the dried soil, which in this case we shall assume to be 1.3 Mg/m^3. In other words, a cubic meter of this soil (*when dry*) has a mass of 1300 kg. From the above calculations we know that the mass of water associated with this 1300 kg of dry soil is 0.428 × 1300 or 556 kg.

Since 1 m^3 of water has a mass of 1000 kg, the 556 kg of water will occupy 556/1000 or 0.556 m^3.

Thus, the volume water content is 0.556 m^3/m^3 of dry soil:

$$\frac{1300 \text{ kg soil}}{\text{m}^3 \text{ soil}} \times \frac{\text{m}^3 \text{ water}}{1000 \text{ kg water}} \times \frac{0.428 \text{ kg water}}{\text{kg soil}} = \frac{0.556 \text{ m}^3 \text{ water}}{\text{m}^3 \text{ soil}}$$

Assuming a soil that does not swell when wet, the relationship between the mass and volume water contents can be summarized as:

$$\theta_v = D_b \times \theta_m \tag{5.7}$$

Neutron Scattering. A **neutron scattering** probe, which is lowered into the soil via a previously installed access tube, contains a source of fast neutrons and a detector for slow neutrons. When fast neutrons collide with hydrogen atoms (most of which are part of water molecules), the neutrons slow down and scatter. The number of slow neutrons counted by a detector corresponds to the soil water content (see Table 5.2).

Dielectric Methods. A dielectric material is poor at conducting an electric current, but can support an electrostatic field (something like a magnetic field). Instruments that measure the dielectric properties of soil can be used to determine the proportion of the soil volume comprised of water because the dielectric constant for water (81) is far greater than for mineral particles (3–5) or for air (1). Therefore, the dielectric constant for the whole soil is nearly proportional to the volume of water in the soil in the immediate vicinity (3–4 cm) of the sensor.

A widely used dielectric method is **time-domain reflectometry** (TDR), which measures two parameters: (1) the time it takes for an electromagnetic impulse to travel down two or three parallel metal transmission rods (wave guides) buried in the soil, and (2) the degree of dissipation of the impulse as it impacts with the soil at the end of the lines. The transit time is related to the soil's apparent dielectric constant (its insulating properties as compared to a vacuum). The dissipation of the signal is related to the level of salts in the soil solution. Thus, both soil *moisture content* and *salinity* can be measured using TDR.

The TDR wave guides may be portable (inserted into the soil for each reading) or may be installed in the soil at various depths and connected by wire to a meter or data logger. The TDR instrument incorporates sophisticated electronics and computer software capable of measuring and interpreting minute voltage changes over precise picosecond time intervals (Figure 5.16). While quite expensive, the TDR instrument can be used (without soil-specific calibration) in most types of soils to obtain accurate readings for the entire range of soil water contents.

Capacitance Methods. By measuring the rate of change of voltage along a thin metal rod, a capacitance sensor determines the dielectric constant of the soil in which it is embedded.

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Table 5.2
SOME METHODS OF MEASURING SOIL WATER
More than one method may be needed to cover the entire range of soil moisture conditions.

	Measures soil water			Used mainly in		
Method	**Content**	**Potential**	**Useful range, kPa**	**Field**	**Lab**	**Comments**
1. Gravimetric	x		0 to < −10,000		x	Destructive sampling; slow (1–2 days) unless microwave used. The standard for calibration.
2. Neutron scattering	x		0 to < −1,500	x		Radiation permit needed; expensive equipment; not good in high-organic-matter soils; requires access tube.
3. Time domain reflectometry (TDR)	x		0 to < −10,000	x	x	Can be automated; accurate to ±1 to 2% volumetric water content; very sandy, clayey, or salty soils need separate calibration; requires wave guides; expensive instrument.
4. Capacitance	x		0 to < −1,500	x		Can be automated; accurate to ±2 to 4% senses volumetric water content; sands or salty soils need special calibration; simple, inexpensive sensors and recording instruments.
5. Resistance blocks		x	−90 to < −1,500	x		Can be automated; not sensitive near optimum plant water contents, may need calibration.
6. Tensiometer		x	0 to −85	x		Can be automated; accurate to ±0.1 to 1 kPa; limited range; inexpensive; needs periodic servicing to add water to tensiometer.
7. Thermocouple psychrometer		x	50 to < −10,000	x	x	Moderately expensive; wide range; accurate only to ±50 kPa.
8. Pressure membrane apparatus		x	50 to < −10,000		x	Used with gravimetric method to construct drier part of water characteristic curve.
9. Tension table		x	0 to −50		x	Used with gravimetric method to construct wetter part of water characteristic curve.

As in the case of the TDR method, variations in measured dielectric constant are mainly due to variations in volumetric water content of the soil. Capacitance sensors are less expensive than neutron or TDR probes and simpler to use. They also do not use hazardous radiation (as does the neutron probe). The sensors are normally accurate to within 3 to 5%, but can be influenced by changes in temperature and salinity, as well as air gaps that occur in very coarse sandy or gravelly soils. Capacitance instruments usually come preprogrammed with separate calibration equations for use in mineral soils, peat potting mixes, or coarse sands, but still, soil-specific calibration may be required for accurate results. Many such probes can be hooked up to a dataloggers to automatically record soil water at many locations within a soil, as well as changes over time.

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Figure 5.16 *Electronic instruments can measure volumetric water content of soil by determining dielectric (insulating) properties of the soil into which a sensor is inserted. A time domain reflectometry (TDR) meter, and sensor* (left) *and a capacitance sensor and meter* (right) *are shown. The TDR instrument calculates the volumetric water content of soil by analyzing the velocity at which electromagnetic waves move through the soil and and the reflected wave patterns generated. Electrical capacitance probes determine volumetric water content by measuring the amount of charge required to raise the voltage between two conductors separated by the soil. The capacitance instruments are simpler and less expensive than the TDR instruments, but are more likely to require laborious soil-specific calibration. For both methods it is important that the sensors be installed such that the prongs are completely and snugly buried in soil with no air gap.* (Photos courtesy of Ray R. Weil)

Measuring Soil Water Potentials

Tensiometers. The tenacity with which water is attracted to soil particles is an expression of matric water potential ψ_m. Field **tensiometers** (Figure 5.17) measure this attraction or *tension*. The tensiometer is basically a water-filled tube closed at the bottom with a porous ceramic cup and at the top with an airtight seal. Once placed in the soil, water in the tensiometer moves through the porous cup into the adjacent soil until the water potential in the tensiometer is the same as the matric water potential in the soil. As the water is drawn out, a vacuum develops under the top seal, which can be measured by a vacuum gauge or an electronic transducer. If rain or irrigation rewets the soil, water will enter the tensiometer through the ceramic tip, reducing the vacuum or tension recorded by the gauge.

Tensiometers are useful between 0 and −85 kPa potential, a range that includes half or more of the water stored in most soils. As the soil dries beyond −80 to −85 kPa, tensiometers fail because air is drawn in through the pores of the ceramic, relieving the vacuum. A solenoid switch can be fitted to a field tensiometer in order to automatically turn an irrigation system on and off.

Electrical Resistance Blocks. Electrical resistance blocks are made of porous gypsum ($CaSO_4 \cdot 2H_2O$), suitably embedded with electrodes. When placed in moist soil, the fine pores in the block absorb water in proportion to the soil water potential. The more tightly the water is being held in the soil, the less water the block will be able to absorb. The resistance to flow of electricity between the electrodes embedded in the block decreases in proportion to how much water has been absorbed in the block (Figure 5.17). These devices must be calibrated for each soil and the accuracy and range of soil moisture contents measured are limited (Table 5.2). However, they are very inexpensive and can be used to measure approximate changes in soil moisture during one or more growing seasons. It is possible to connect them to data loggers or electronic switches so that irrigation systems can be turned on and off automatically at set soil moisture levels.

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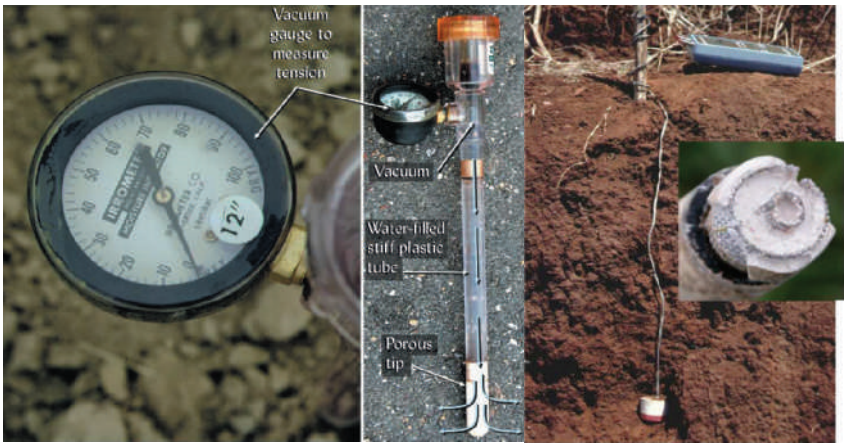

Figure 5.17 *Instruments that measure soil water potential in the field include the tensiometer (center) and electrical resistance blocks (right). The tensiometer tube is filled with water through the screw-off top. Once the instrument is tightly sealed, the white porous tip and the lower part of the plastic tube is inserted into a snug-fitting hole in the soil. The vacuum gauge (close up, left) will directly indicate the tension or negative potential generated as the soil draws the water out (curved arrows) through the porous tip. Note the scale goes up to only 100 centibars (= 100 kPa) tension at the driest. (Right) A cutaway view of soil with a commercial gypsum electrical resistance block installed about 45 cm below the surface. Thin wires lead from the block to the surface, where they can be connected to a special resistance meter. Another gypsum block has been broken open (inset) to reveal two concentric metal screen cylinders that serve as the electrodes between which moistened gypsum conducts a small electric current. The resistance to current flow is inversely proportional to the wetness of the gypsum block.* (Photos courtesy of Ray R. Weil)

Thermocouple Psychrometer. Since plant roots must overcome both matric and osmotic forces when they draw water from the soil, there is sometimes a need for an instrument that measures both. The relative humidity of soil air is affected by both matric and osmotic forces, for both constrain the escape of water molecules from liquid water. In a thermocouple psychrometer, a voltage generated by the evaporation of a water drop is converted into a readout of soil water potential ($\psi_o + \psi_m$). The thermocouple psychrometer is most useful in relatively dry soils in which imprecisions of ±50 kPa involve negligible quantities of water.

Pressure Membrane Apparatus. A pressure membrane apparatus (Figure 5.18) is used to subject soils to matric potentials as low as −10,000 kPa. After application of a specific matric potential to a set of soil samples, their soil water contents are determined gravimetrically. This important laboratory tool makes possible accurate measurement of water content over a wide range of matric potentials in a relatively short time. It is used, along with the tension plate, to obtain data to construct soil water characteristic curves such as those shown in Figure 5.12.

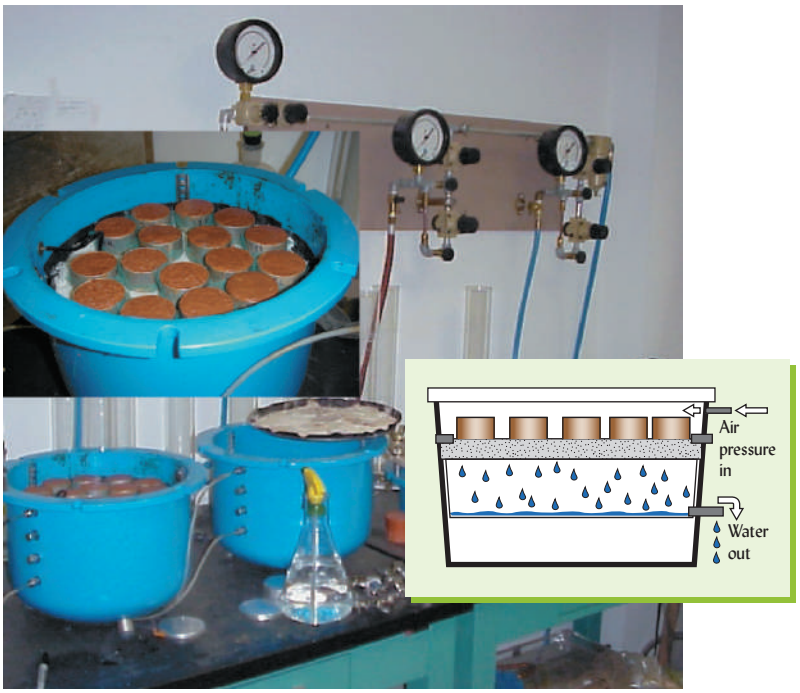

Figure 5.18 *Pressure membrane apparatus used to determine relationships between water content and matric potential in soils. An outside source of gas creates a pressure inside the sealed chamber. Water is forced out of the soil through a porous plate* (see inset diagram) *into a cell at atmospheric pressure. The inset photo* (upper left) *shows a top view of soil samples contained in metal rings set on the porous plate before bolting on the cover. The pressure applied when the downward flow of water ceases reflects the water potential in the soil. This apparatus will measure much lower soil water potential values (drier soils) than will tensiometers.* (Photos and diagram courtesy of Ray R. Weil)

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5.5 THE FLOW OF LIQUID WATER IN SOIL

Water movement within the soil occurs as: (1) saturated flow, (2) unsaturated flow, and (3) vapor movement.[7] In all cases water flows in response to energy gradients, with water moving from a zone of higher to one of lower water potential. *Saturated flow* takes place when the soil pores are completely filled (or saturated) with water. *Unsaturated flow* occurs when the larger pores in the soil are filled with air, leaving only the smaller pores to hold and transmit water. *Vapor movement* occurs as vapor pressure differences develop in relatively dry soils.

Saturated Flow Through Soils

Under some conditions, at least part of a soil profile may be completely saturated; that is, all pores, large and small, are filled with water. The lower horizons of poorly drained soils are often saturated, as are portions of well-drained soils above water restricting layers of clay. During and immediately following a heavy rain or irrigation, pores in the upper soil zones are often filled entirely with water.

The quantity of water per unit of time Q/t that flows through a column of saturated soil (Figure 5.19) can be expressed by Darcy's law, as follows:

$$\frac{Q}{t} = AK_{sat}\frac{\Delta\psi}{L} \tag{5.8}$$

where A is the cross-sectional area of the column through which the water flows, K_{sat} is the **saturated hydraulic conductivity**, $\Delta\psi$ is the change in water potential between the ends of the column (e.g., $\psi_1 - \psi_2$), and L is the length of the column. For a given column, the rate of flow is determined by the ease with which the soil transmits water (K_{sat}) and the amount of force driving the water, namely, the **water potential gradient** $\Delta\psi/L$. For saturated flow, this force may also be called the **hydraulic gradient**. By analogy, think of pumping water through a garden hose, with K_{sat} representing the size of the hose (water flows more readily through a larger hose) and $\Delta\psi/L$ representing the size of the pump that drives the water through the hose.

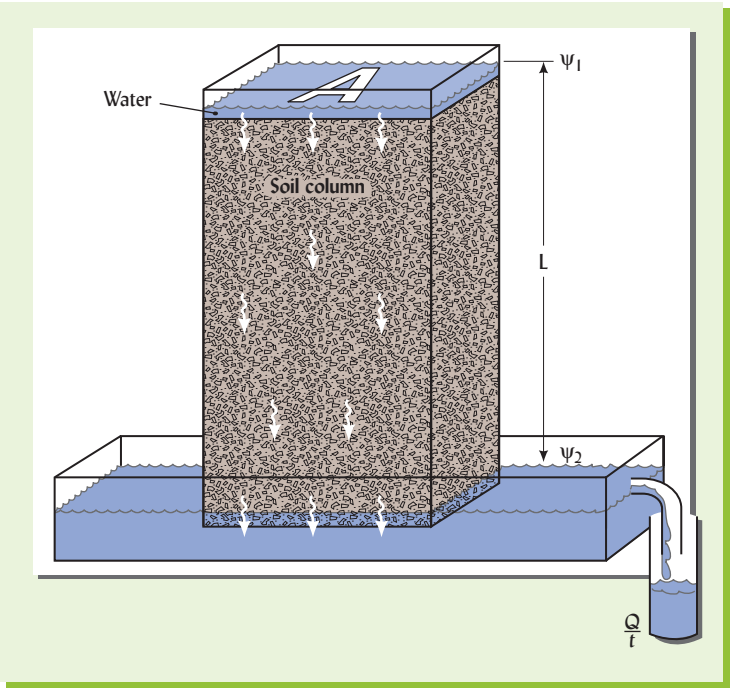

Figure 5.19 *Saturated flow (percolation) in a column of soil with cross-sectional area A, cm^2. All soil pores are filled with water. At lower right, water is shown running off into a container to indicate that water is actually moving down the column. The force driving the water through the soil is the water potential gradient, $\psi_1 - \psi_2/L$, where both water potentials and length are expressed in cm (see Table 5.1). If we measure the quantity of water flowing out Q/t as cm^3/s we can rearrange Darcy's law (from eq. 5.8) to calculate the saturated hydraulic conductivity of the soil K_{sat} in cm/s as:*

$$K_{sat} = \frac{Q}{A \cdot t}\frac{L}{\psi_1 - \psi_2} \tag{5.9}$$

Remember that the same principles apply where the water potential gradient moves the water in a horizontal direction.

[7] A fourth type of flow, **hydraulic redistribution** by plants can move significant amounts of water in the soil profile but occurs within the plant roots rather than in the soil, per se, will be considered in Section 6.3.

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The units in which K_{sat} is measured are length/time, typically cm/s or cm/h. The K_{sat} is an important property that helps determine how well a soil or soil material will perform in such uses as irrigated cropland, sanitary landfill cover material, wastewater storage lagoon lining, and septic tank drain fields (Table 5.3).

It should not be inferred from Figure 5.19 that saturated flow occurs only down the profile. The hydraulic force can also cause horizontal and even upward flow, as occurs when groundwater wells up under a stream (see Section 6.6). The rate of such flow is usually not quite as rapid, however, since the force of gravity does not assist horizontal flow and hinders upward flow. Downward and horizontal flows are illustrated in Figure 5.20, which records the flow of water from an irrigation furrow into two soils, a sandy loam and a clay loam. The water moved down much more rapidly in the sandy loam than in the clay loam. On the other hand,

Table 5.3
SOME APPROXIMATE VALUES OF SATURATED HYDRAULIC CONDUCTIVITY (IN VARIOUS UNITS) AND INTERPRETATIONS FOR SOIL USES

K_{sat}, cm/s	K_{sat}, cm/h	K_{sat}, in/h	Comments
1×10^{-2}	36	14	Typical of beach sand.
5×10^{-3}	18	7	Typical of very sandy soil, too rapid to effectively filter pollutants in wastewater.
5×10^{-4}	1.8	0.7	Typical of moderately permeable soils, K_{sat} between 1.0 and 15 cm/h considered suitable for most agricultural, recreational, and urban uses calling for good drainage.
5×10^{-5}	0.18	0.07	Typical of fine-textured, compacted, or poorly structured soils. Too slow for proper operation of septic tank drain fields, most types of irrigation, and many recreational uses such as playgrounds.
$< 1 \times 10^{-8}$	$< 3.6 \times 10^{-5}$	$< 1.4 \times 10^{-5}$	Extremely slow; typical of compacted clay. K_{sat} of $10^{-5} - 10^{-8}$ cm/h may be required where nearly impermeable material is needed, as for lagoon lining or landfill cover material.

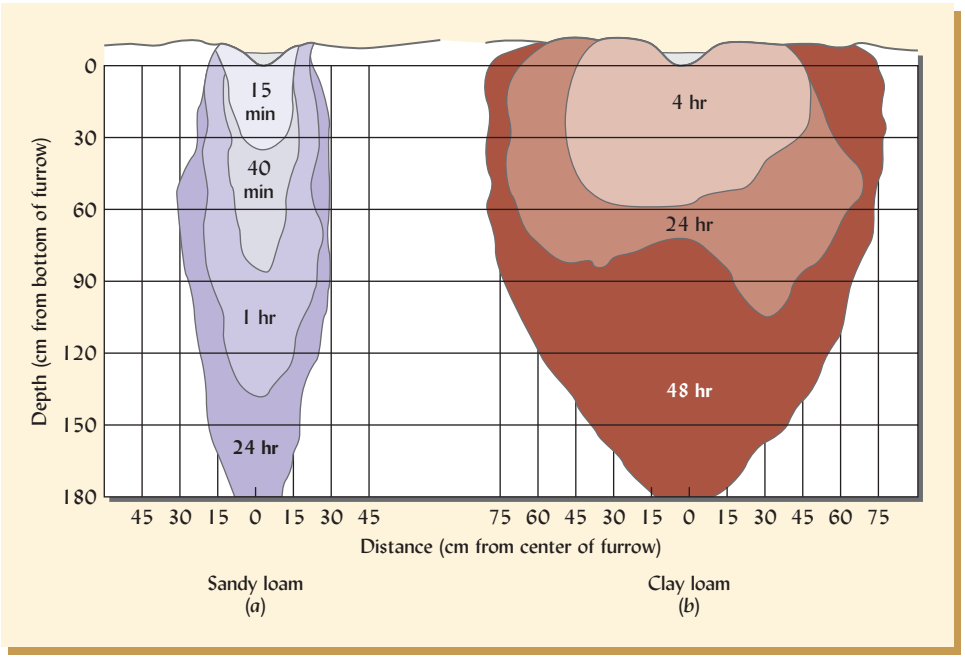

Figure 5.20 *Movement of irrigation water into a sandy loam and a clay loam. Note the much more rapid and downward focused movement in the sandy loam in comparison to the slower, but more horizontal movement into the clay loam.* [Redrawn from Cooney and Peterson (1955)]

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horizontal movement (which would have been largely by unsaturated flow) was much more evident in the clay loam.

Factors Influencing the Hydraulic Conductivity of Saturated Soils

Macropores. Any factor affecting the size and configuration of soil pores will influence hydraulic conductivity. The total flow rate in soil pores is proportional to the fourth power of the radius. Thus, flow through a pore 1 mm in radius is equivalent to that in 10,000 pores with a radius of 0.1 mm (even though it takes only 100 pores of radius 0.1 mm to give the same cross-sectional area as a 1 mm radius pore). As a result, macropores (radius >0.08 mm) account for nearly all water movement in saturated soils (see Table 5.4). Because they usually have more macropore space, sandy soils generally have higher saturated conductivities than finer-textured soils. Likewise, soils with stable structure conduct water much more rapidly through interped cracks and pores than do those with unstable structural units, which break down upon being wetted. However, air trapped in rapidly wetted soils can block pores and thereby reduce hydraulic conductivity. Similarly, the *interconnectedness* of pores is important, as noninterconnected pores are like "dead-end streets" to flowing water. Vesicular pores in certain desert soils are examples (Figure 3.26).

Biopores, such as root channels and earthworm burrows (typically >1 mm in radius), are a special type of macropore and their presence has a marked influence on the saturated hydraulic conductivity of different soil horizons (Table 5.5 and Figure 4.55). Perennial vegetation creates a network of stable biopores while tillage for production of annual plants destroys these pores and cuts them off from the soil surface. Therefore, saturated conductivities of soils under perennial grassland or forest vegetation is commonly much greater than where annual crop plants are cultivated, and among cultivated soils, saturated hydraulic conductivity is usually greater under no-tillage management than under conventional tillage.

Table 5.4
NUMBER OF MACROPORES IN THREE SIZE CLASSES, THEIR PROPORTION OF THE SOIL POROSITY AND THEIR CONTRIBUTION TO TOTAL WATER FLOW IN AN IRRIGATED MAIZE FIELD[a]

Most of the flow took place through the largest class of pores even though the smaller pores were far greater in number and in percent of the total soil porosity. Note that only 5.5% of the total soil porosity is considered here, the other 94.5% being comprised of pores smaller than 0.1 mm.

	Effective pore radius,[b] mm		
	>0.5	0.5–0.25	0.25–0.1
	Large macropores	Small macropores[c]	
Number of pores, m^2	235	167	2200
% of effective porosity	3.1	------ 2.4 ------	
% of flow	88	9	3

[a]The data pertain to the upper 30 cm of a Fluvent with a silt loam texture in Southern Portugal. Maize was planted on permanent ridges with furrow irrigation and minimum tillage.

[b]A disk infiltrometer was used to maintain tensions of 0.3, 0.6, and 1.5 kPa to exclude flow in pores with diameters >0.5, 0.25, and 0.1 mm, respectively.

[c]Although the original paper refers to these pores as "mesopores," we use the term "small macropores," to be consistent with the classes in Table 4.5.

[Data calculated from Cameira et al. (2003)]

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Table 5.5
THE SATURATED HYDRAULIC CONDUCTIVITY K_{SAT} AND RELATED PROPERTIES OF VARIOUS HORIZONS IN A TYPIC HAPLUDULT PROFILE

The upper horizons had many biopores (mainly earthworm burrows), which resulted in high values of K_{sat} as well as extreme variability from sample to sample. The presence of a clay-enriched argillic horizon resulted in reduced K_{sat} values. Apparently most large biopores in this soil did not extend below 30 cm.

Horizon	Depth, cm	Clay, %	Bulk density, Mg/m^3	Mean K_{sat}, cm/h	Range of K_{sat} values,[a] cm/h
Ap	0–15	12.6	1.42	22.4	0.80–70
E	15–30	11.1	1.44	7.9	0.50–24
E/B	30–45	14.5	1.47	0.93	0.53–1.33
Bt	45–60	22.2	1.40	0.49	0.19–0.79
Bt	60–75	27.2	1.38	0.17	0.07–0.27
Bt	75–90	24.1	1.28	0.04	0.01–0.07

[a]For each soil layer K_{sat} was determined on five soil cores of 7.5 cm diameter.
[Data from Waddell and Weil (1996)]

Preferential Flow. Scientists have been surprised to find more extensive pollution of groundwater from pesticides and other toxicants than would be predicted from traditional hydraulic conductivity measurements that assume uniform soil porosity. Apparently solutes (dissolved substances) are carried downward rapidly by water that moves through large macropores such as cracks and biopores, often before the bulk of the soil is thoroughly wetted. Mounting evidence suggests that this type of nonuniform water movement, referred to as **preferential flow**, greatly increases the chances of groundwater pollution (see Figure 5.21).

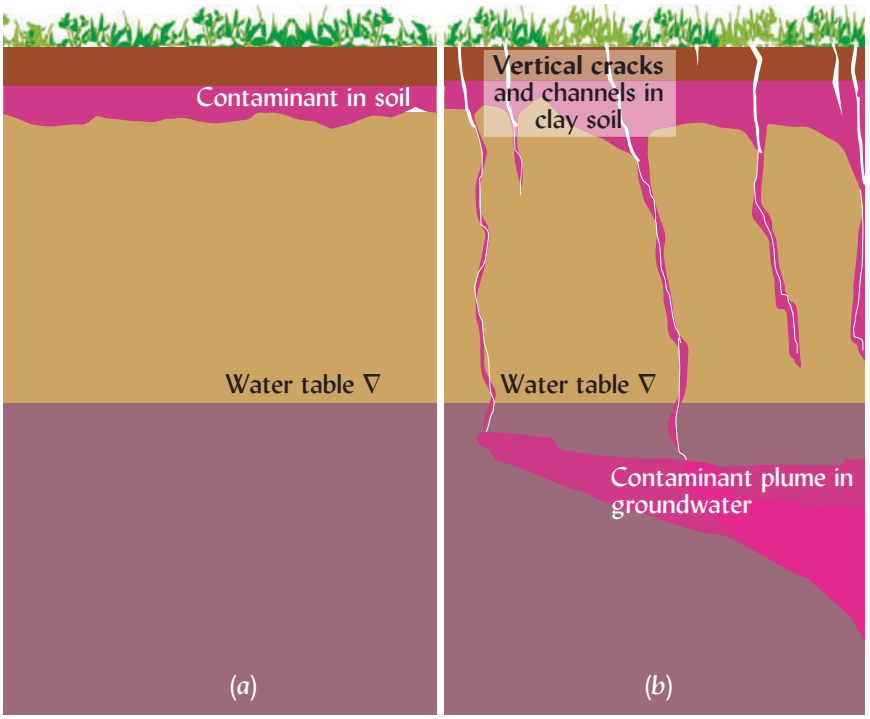

Figure 5.21 *An illustration of preferential flow of water and surface contaminant downward to the water table. A toxic material was spilled on the clayey soil alongside a highway. Environmental officials assumed there would be slow uniform movement of water and the contaminant through the soil* (a), *and therefore they did not expect downward movement into the water table to pose a serious problem as the chemical would degrade before it reached the water table. The officials were surprised to find groundwater contamination soon after the spill. The contaminant quickly reached the water table via macropores made by the cracking of swelling clay as the deep-rooted vegetation dried the soil* (b). *Because of these cracks, the first heavy rain after the spill carried the chemical into the groundwater by preferential before the soil could swell and shut the cracks.* (Diagram courtesy of Ray R. Weil)

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Preferential flow in fine-textured soils is enhanced by clay shrinkage, which leaves open cracks and fissures that can extend down into the lower subsoil horizons. In some clay soils, water from the first rain storm after a dry spell moves rapidly down the profile, carrying with it soluble pesticides or nutrients that may be on the soil surface (Table 5.6). Recognition that heterogeneity of field soils leads to preferential flow is stimulating more aggressive approaches to controlling groundwater contamination. When chemicals and animal wastes are applied to the soil surface, transport of chemicals and fecal bacteria by preferential flow can threaten human health, as well as environmental quality.

Macropores with continuity from the soil surface down through the profile encourage preferential flow. Burrowing animals (e.g., worms, rodents, and insects) as well as decayed plant roots leave tubular channels through which water can flow rapidly. In very sandy soils, hydrophobic organic coatings on sand grains repel water, preventing it from soaking in uniformly. Where these coatings are absent or wear off, water rapidly enters and produces "fingers" of rapid wetting (see Figure 5.22). This "finger flow" probably is responsible for the finger-like shapes of the spodic horizon in some Spodosol profiles (e.g., Figure 3.29).

Table 5.6
LEACHING OF PESTICIDES BY PREFERENTIAL FLOW IN A SLOWLY PERMEABLE ALFISOL
Most leaching took place following the first major storm of the year.

	Leaching of pesticide applied, % (3 year average)		
Chemical	**First storm**	**Spring season**	**First storm/spring season total, %**
Carbofuran	0.22	0.25	88
Atrazine	0.037	0.053	68
Cyanazine	0.02	0.02	100

[Calculated from Kladivko et al. (1999)]

Figure 5.22 *Finger flow—the uneven infiltration into and flow through sandy soils caused by hydrophobic organic coatings on sand grains. Credit card shown to left for scale.* (Photo courtesy of Stefan Doerr, University of Swansea, Wales, UK)

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Fingering also occurs in stratified sandy layers that underlie finer-textured materials (see Section 5.6).

Unsaturated Flow in Soils

Most of the time, water movement takes place when upland soils are *unsaturated*. Such movement occurs in a more complicated environment than that which characterizes saturated water flow. In saturated soils, essentially all the pores are filled with water, although the most rapid water movement is through the large and continuous pores. But in unsaturated soils, these macropores are filled with air, leaving only the finer pores to accommodate water movement (Figure 5.23). Also, in unsaturated soils the water content and, in turn, the tightness with which water is held (water potential) can be highly variable. This influences the rate and direction of water movement and also makes it more difficult to measure the flow of soil water.

As was the case for saturated water movement, the driving force for unsaturated water flow is differences in water potential. This time, however, the difference in the matric potential, not gravity, is the primary driving force. This **matric potential gradient** is the difference in the matric potential of the moist soil areas and nearby drier areas into which the water is moving. Movement will be from a zone of thick moisture films (high matric potential, e.g., −1 kPa) to one of thin films (lower matric potential, e.g., −100 kPa). Generally, if a dry soil is wetted (e.g., by a slow leak in a buried water pipe), water will flow in all directions from the wet soil into the adjacent dry soil. This flow will be rapid at first, but then will slow down as the initially large matric potential gradient declines. The gradient declines mainly because the zone of wettest soil and the as yet unwetted dry soil zone become farther apart as the water advances—that is, the distance L in Eq. (5.8) become greater, thus reducing the potential gradient $\Delta\psi/L$.

Influence of Texture. Figure 5.24 shows the general relationship between matric potential ψ_m (and, in turn, water content) and hydraulic conductivity of a sandy loam and clay soil. Note that at or near zero potential (which characterizes the saturated flow region), the hydraulic conductivity is thousands of times greater than at potentials that characterize typical unsaturated flow (−10 kPa and below).

At high potential levels (high moisture contents), hydraulic conductivity is higher in the sand than in the clay. The opposite is true at low potential values (low moisture contents). This relationship is to be expected because the sandy soil contains many large pores that are water-filled when the soil water potential is high (and the soil is quite wet), but most of these have been emptied by the time the soil water potential becomes lower than about −10 kPa. The clay soil has many more micropores that are still water-filled at lower soil water potentials (drier soil conditions) and can participate in unsaturated flow.

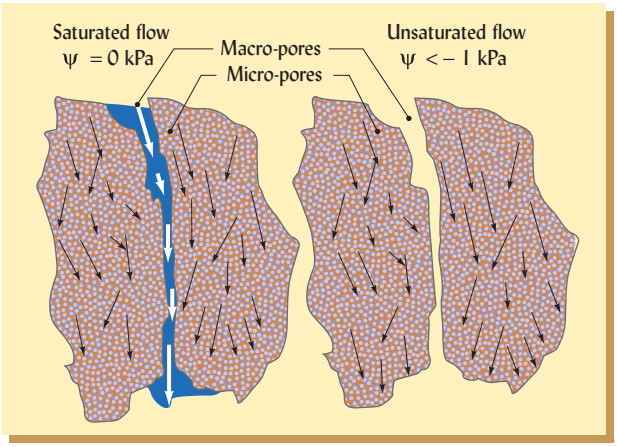

Figure 5.23 *Schematic comparison of saturated and unsaturated water flow in soils. Note that when the water potential is even slightly negative, large macropores will have drained empty of water and therefore cannot contribute to water flow.* (Diagram courtesy of Ray R. Weil)

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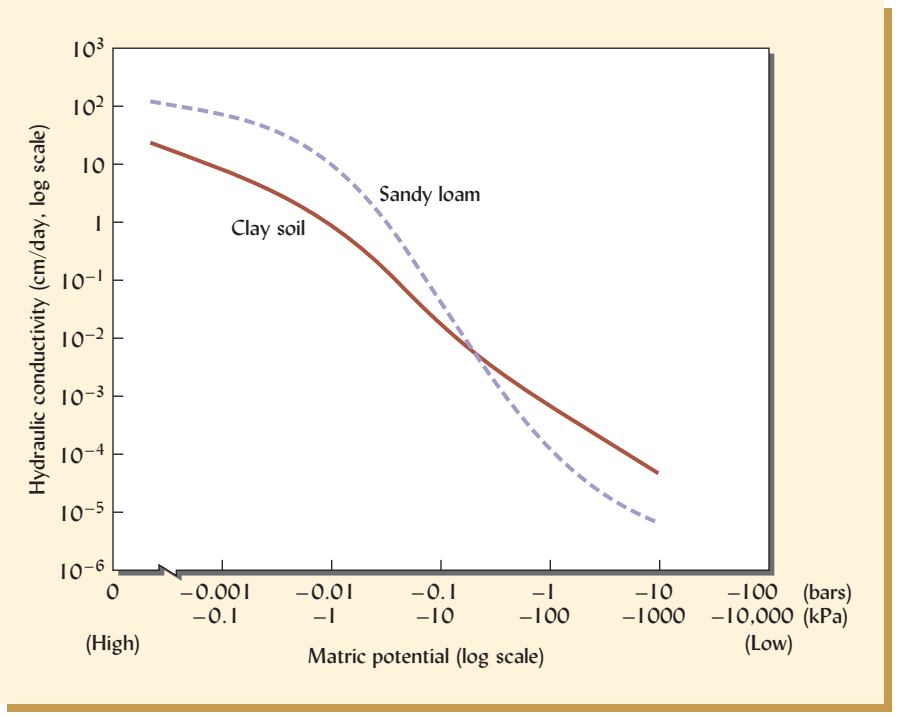

Figure 5.24 *Generalized relationship between matric potential and hydraulic conductivity for a sandy soil and a clay soil (note log scales). Saturated flow takes place at or near zero potential, while much of the unsaturated flow occurs at a potential of −0.1 bar (−10 kPa) or below.*

5.6 INFILTRATION AND PERCOLATION

A special case of water movement is the entry of free water into the soil at the soil–atmosphere interface. As we shall explain in Chapter 6, this is a pivotal process in landscape hydrology that greatly influences the moisture regime for plants and the potential for soil degradation, chemical runoff, and down-valley flooding. The free water at the soil surface may be from rainfall, snowmelt, irrigation, or a liquid chemical spill.

Infiltration

The process by which water enters the soil pore spaces and becomes soil water is termed *infiltration*, and the rate at which water can enter the soil is termed the *infiltrability i:*

$$i = \frac{Q}{A \times t} \tag{5.10}$$

where Q is the volume quantity of water (m^3) infiltrating, A is the area of the soil surface (m^2) exposed to infiltration, and t is time (s). Since m^3 appears in the numerator and m^2 in the denominator, the units of infiltration can be simplified to m/s or, with appropriate conversions, to cm/h. The infiltration rate is not constant over time, but generally decreases during an irrigation or rainfall episode. If the soil is quite dry when infiltration begins, all the macropores open to the surface will be available to conduct water into the soil. In soils with expanding types of clays, the initial infiltration rate may be particularly high as water pours into the network of shrinkage cracks. However, as infiltration proceeds, many macropores fill with water, and shrinkage cracks close up. The infiltration rate declines sharply at first and then tends to level off, remaining fairly constant thereafter (Figure 5.25).

Measurement. The infiltration capacity of a soil may be easily measured using a simple device known as an **infiltrometer**. One common type is the falling head **double ring infiltrometer** which is comprised of two heavy metal cylinders, one smaller in diameter than the other, that are pressed partially into the soil so that the smaller is inside the larger (see

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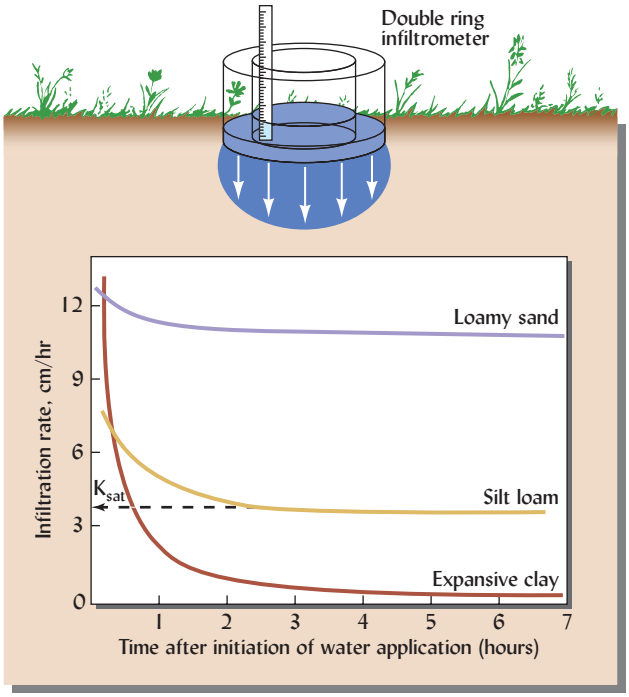

Figure 5.25 *The potential rate of water entry into the soil, or infiltration capacity, can be measured by recording the drop in water level in a double ring infiltrometer* (top). *Changes in the infiltration rate of several soils during a period of water application by rainfall or irrigation are shown* (bottom). *Generally, water enters a dry soil rapidly at first, but its infiltration rate slows as the soil becomes saturated. The decline is least for very sandy soils with macropores that do not depend on stable structure or clay shrinkage. In contrast, a soil high in expansive clays may have a very high initial infiltration rate when large cracks are open, but a very low infiltration rate once the clays swell with water and close the cracks. Most soils fall between these extremes, exhibiting a pattern similar to that shown for the silt loam soil. The dashed arrow indicates the level of* K_{sat} *for the silt loam illustrated.*
(Diagram courtesy of Ray R. Weil)

Figure 5.25). A layer of cheesecloth is placed inside the rings to protect the soil surface from disturbance, and water is poured into both cylinders. The depth of water in the central cylinder is then recorded periodically as the water infiltrates the soil. The water infiltrating in the outer cylinder is not measured, but it ensures that the surrounding soil will be equally moist and that the movement of water from the central cylinder will be principally downward, not horizontal.

Percolation

Infiltration is a transitional phenomenon that takes place at the soil surface. Once the water has infiltrated the soil, the water moves downward into the profile by the process termed **percolation**. Both saturated and unsaturated flow are involved in percolation of water down the profile, and rate of percolation is related to the soil's hydraulic conductivity. In the case of water that has infiltrated a relatively dry soil, the progress of water movement can be observed by the darkened color of the soil as it becomes wet (Figure 5.26). There usually appears to be a sharp boundary, termed a **wetting front**, between the dry underlying soil and the soil already wetted. During an intense rain or heavy irrigation, water movement near the soil surface occurs mainly by saturated flow in response to gravity. At the wetting front, however, water is moving into the underlying drier soil in response to matric potential gradients as well as gravity. During a light rain, both infiltration and percolation may occur mainly by unsaturated flow as water is drawn by matric forces into the fine pores without accumulating at the soil surface or in the macropores.

Water Movement in Stratified Soils

The fact that, at the wetting front, water is moving by unsaturated flow has important ramifications for how percolating water behaves when it encounters an abrupt change in pore sizes due to such layers as fragipans or claypans, or sand and gravel lenses. In some cases, such pore-size stratification may be created by soil managers, as when coarse plant residues are plowed under in a layer or a layer of gravel is placed under finer soil in a planting container. In all cases, the effect on water percolation is similar—that is, the downward movement is impeded—even though the causal mechanism may vary. The contrasting layer acts as a barrier

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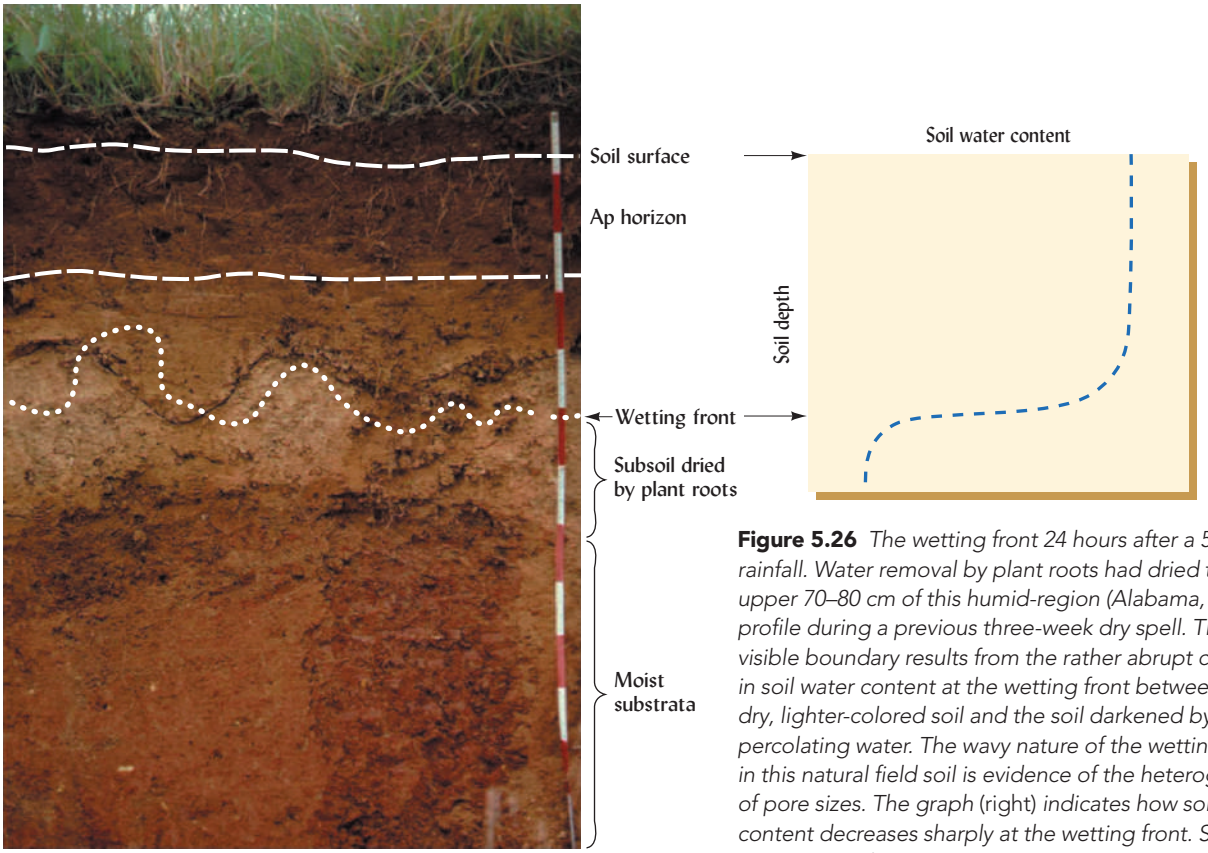

Figure 5.26 *The wetting front 24 hours after a 5 cm rainfall. Water removal by plant roots had dried the upper 70–80 cm of this humid-region (Alabama, USA) profile during a previous three-week dry spell. The clearly visible boundary results from the rather abrupt change in soil water content at the wetting front between the dry, lighter-colored soil and the soil darkened by the percolating water. The wavy nature of the wetting front in this natural field soil is evidence of the heterogeneity of pore sizes. The graph* (right) *indicates how soil water content decreases sharply at the wetting front. Scale in 10 cm intervals.* (Photo courtesy of Ray R. Weil)

to water flow and results in much higher field-moisture levels above the barrier than what would normally be encountered in freely drained soils. It is not surprising that percolating water should slow down markedly when it reaches a layer with finer pores, which therefore has a lower hydraulic conductivity. However, the fact that a layer of *coarser* pores will temporarily stop the movement of water may not be obvious.

In Figure 5.27, a layer of coarse sand underlies a fine-textured soil. Intuitively, one might expect the sand layer to speed the downward percolation of water. However, the coarser sand layer has just the opposite effect; it actually impedes the flow of water. The macropores of the sand offer less attraction for the water than do the finer pores of the overlying material. Since water always moves from higher to lower potential (to where it will be held more tightly), the wetting front cannot move readily into the sand. If it cannot move laterally, as it would in the case of a sloping coarse layer, the downward-moving water will eventually accumulate above the sand layer and saturate the pores at the soil–sand interface. The matric potential of the water at the wetting front will then fall to nearly zero or even become positive. Once this occurs, the water will be so loosely held by the fine-textured soil that gravity or hydrostatic pressure will force the water into the sand layer.

Interestingly, a coarse sand layer in an otherwise fine-textured soil profile would also inhibit the *rise* of water from moist subsoil layers up to the surface soil, a situation that could be illustrated by turning Figure 5.27*b* upside down. The large pores in the coarse layer will not be able to support capillary movement up from the smaller pores in a finer layer. Consequently, water rises by capillarity up to the coarse-textured layer but cannot cross it to supply moisture to overlying layers. Thus, plants growing on some soils with buried gravel lenses are subject to drought since they are unable to exploit water in the lower soil layers. This principle also allows a layer of gravel to act as a capillary barrier under a concrete slab foundation to prevent water from soaking up from the soil and through the concrete floor of a home basement.

The fact that coarse-textured layers (e.g., gravel, sand, coarse organic materials, or geotextile fabrics) can hinder both downward and upward unsaturated flow of water must be

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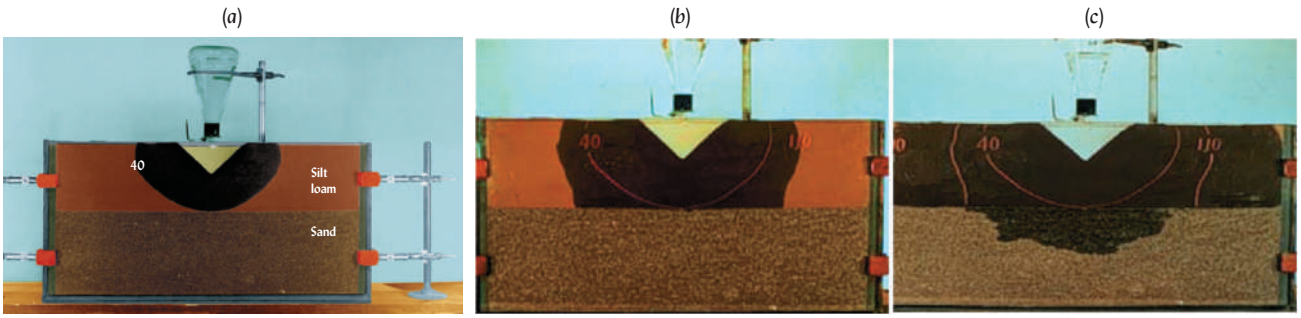

Figure 5.27 *Downward water movement in soils with a stratified layer of coarse material.* (Left) *Water is applied to the surface of a medium-textured topsoil. Note that after 40 min, downward movement is no greater than movement to the sides, indicating that in this case the gravitational force is insignificant compared to the matric potential gradient between dry and wet soil.* (Center) *The* downward *movement stops when a coarse-textured layer is encountered. After 110 min, no movement into the sandy layer has occurred. The macropores of the sand provide less attraction for water than the finer-textured soil above, so the water accumulates and moves laterally above the sand layer.* (Right) *Only when the water content (and in turn the matric potential gradient) is raised sufficiently will the water move into the sand. After 400 min, the water content of the overlying layer becomes sufficiently high to give a water potential close to 0 kPa or slightly positive, and the water breaks through into the coarse material abruptly and unevenly.* (Courtesy W. H. Gardner, Washington State University)

BOX 5.3

PRACTICAL APPLICATIONS OF UNSATURATED WATER FLOW IN CONTRASTING LAYERS

Unsaturated flow is interrupted where soil texture abruptly changes from relatively fine to coarse. Capillary water held tightly by matric attraction in the smaller pores of the finer-textured layer cannot move into the larger pores in the underlying coarser-textured layer unless under positive pressure. That is, a larger pore cannot "pull" water from a smaller pore. In fact, unsaturated water flow always occurs in the reverse direction, from larger to smaller pores. A wetting front moving down a soil profile along the matric potential gradient therefore ceases downward movement when it encounters pores much larger than those through which it has been traversing. Instead of continuing downward, water will move laterally in the finer layer. If water is entering the system more rapidly than lateral capillarity can carry it away, a perched water table may develop above the interface between the two layers (Figure 5.28).

This phenomenon is applied in the design of soil profiles for golf course putting greens. The soil specified for the rooting zone consists almost entirely of sand in order to promote rapid infiltration of water and to resist compaction by foot traffic. However, water normally drains so fast through sand that too little is held to meet the needs of growing grass. This situation is remedied to some extent by constructing the putting green with a layer of gravel underneath the sand rooting zone. The large pores in the gravel temporarily stop the downward movement of water. The resulting perched water table (Figure 5.29) causes the sand layer to retain more water than it would otherwise, but still allows for rapid drainage of excess water—when a buildup of positive pressure allows gravitational forces to override matric forces.

The same principle is at the heart of a design proposed to keep nuclear wastes from contaminating groundwater during the many thousands of years required for the radionuclides to decay to harmless products. One plan was to store radioactive wastes in sealed containers kept

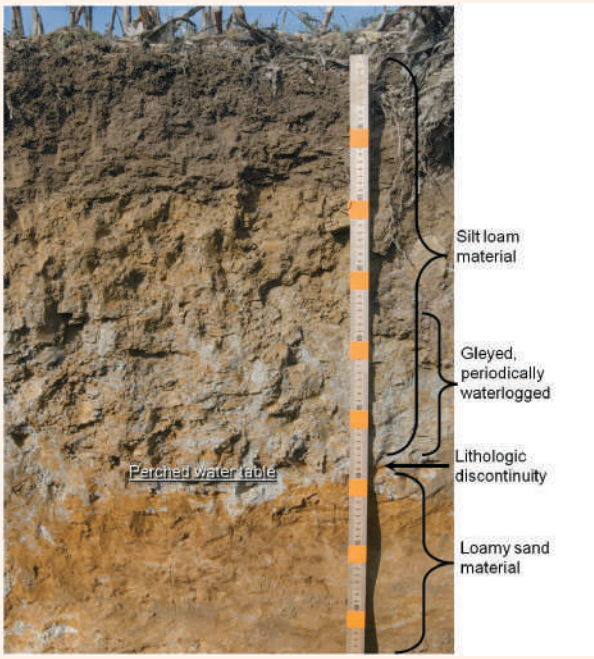

Figure 5.28 *A water-saturated layer resulting from the interruption of water flow where fine soil is underlain by coarser material. Water logging (indicated by the gleyed, gray-colored soil layer) often occurs during wet weather where the silt loam upper layers meet the coarse loamy sand lower layers in this soil profile. Note the reddish colors indicating good oxidation in both the silt loam soil layers above and in the sandy layer below the perched water table.* (Photo courtesy of C. White, The Pennsylvania State University)

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BOX 5.3

PRACTICAL APPLICATIONS OF UNSATURATED WATER FLOW IN CONTRASTING LAYERS *(CONTINUED)*

in caverns carved from the rock deep inside Yucca Mountain in Nevada, USA. Despite its desert location, the Yucca Mountain rock contains large amounts of water in pores and fractures, resulting in water dripping from the ceiling of the storage caverns. Although the containers for the heat-generating wastes were to be as corrosion-resistant as possible, no one believes they would remain intact if exposed to moisture and air for thousands of years. To fend off the dripping water, a huge canopy made of special corrosion-resistant metal alloys was designed. Construction of this canopy over the highly radioactive wastes would be extremely difficult and expensive, with no guarantee that the structure would not deteriorate over the millennia. Therefore, a far easier, less expensive, and more reliable alternative has been proposed. Burying the waste containers under mounds of first gravel and then sand (Figure 5.30) in a texture-stratified system would create a *capillary barrier* to protect the containers. Water dripping into the sand would be held by capillary forces in the relatively small pores between sand grains. As the water enters the sand, it moves by capillary flow along matric potential gradients. Its downward movement would be interrupted when it reached the much larger pores of the gravel layer. The containers would remain dry because both matric potential gradients and gravity would cause the water in the sand layer to move along the curved interface rather than into the gravel layer (arrows in Figure 5.30).

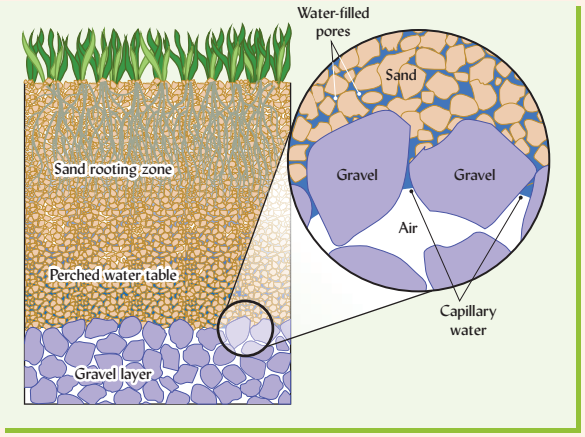

Figure 5.29 *A gravel layer under a putting green is used to increase the water available to turfgrass roots in the sand rooting zone, while allowing rapid drainage if saturation occurs.* (Diagram courtesy of Ray R. Weil)

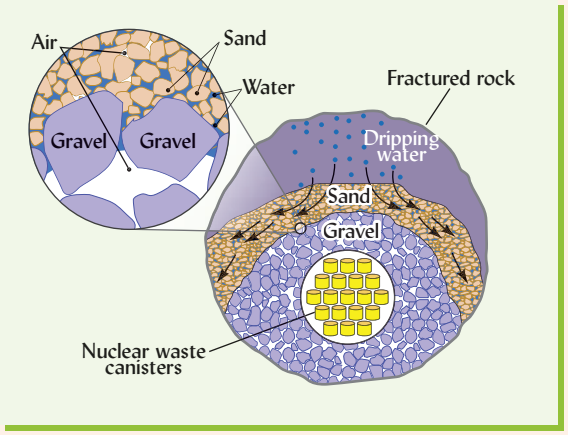

Figure 5.30 *Proposed use of capillary principles to prevent dripping water from corroding toxic nuclear waste containers inside a deep burial site like Yucca Mountain in Nevada, USA, thus protecting groundwater from contamination over hundreds of thousands of years.* [Diagram based on concepts in Carter and Pigford (2005)]

considered—and may be used to advantage—when dealing with such materials in planting containers, landscape drainage schemes (see Section 6.7), or engineering works (see Box 5.3).

5.7 WATER VAPOR MOVEMENT IN SOILS

Two types of water vapor movement are associated with soils, *internal* and *external*. Internal movement takes place within the soil, that is, in the soil pores. External movement occurs at the land surface, and water vapor is lost by surface evaporation (see Section 6.4).

Water vapor moves from one point to another within the soil in response to differences in vapor pressure. Thus, water vapor will move from a moist soil where the soil air is nearly 100% saturated with water vapor (high vapor pressure) to a drier soil where the vapor pressure is somewhat lower. Also, water vapor will move from a zone of low salt content to one with a higher salt content (e.g., around a fertilizer granule). The salt lowers the vapor pressure of the water and encourages water movement from the surrounding soil.

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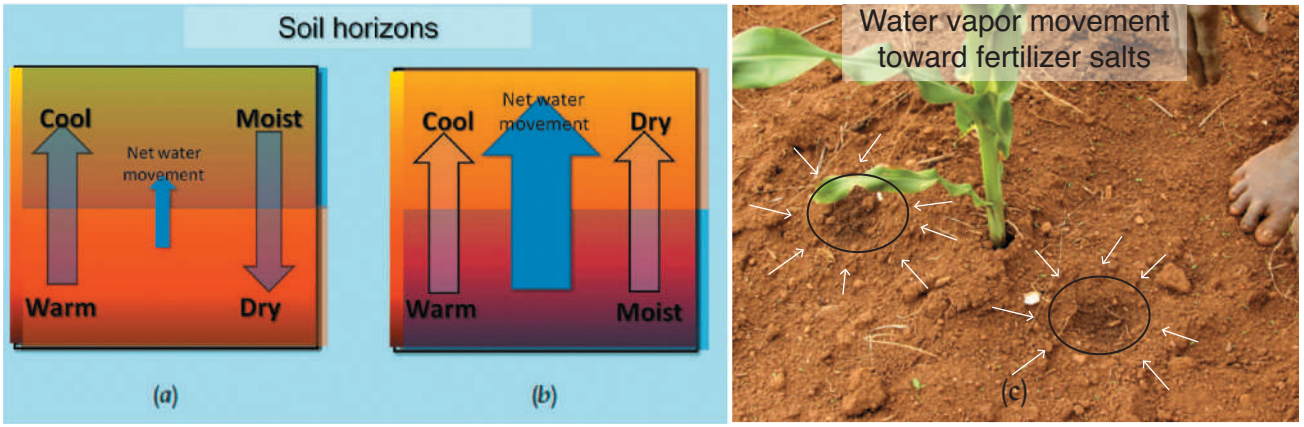

Figure 5.31 *Vapor movement caused by vapor pressure gradients between soil zones differing in temperature, moisture, or salinity. In* (a) *the gradients nearly negate each other, resulting is only a small net vapor pressure gradient and net water vapor movement (small vertical arrow). In* (b) *the moisture and temperature gradients are coordinated, and considerable vapor transfer is expected if the liquid water in the soil capillaries does not interfere. In* (c) *two small spots of soils have been darkened by moisture. Below each of these spots, the African farmer had buried a spoonful of soluble fertilizer in the relatively dry soil. The fertilizer began to dissolve, creating a salty solution with very low water vapor pressure around it, thus setting up a vapor pressure gradient that caused water vapor to move from the nonsalty surrounding soil toward the salty soil where the fertilized had been applied.* (Diagram and photo courtesy of Ray R. Weil)

If the temperature of one part of a uniformly moist soil is lowered, the vapor pressure will decrease and water vapor will tend to move toward this cooler part. Heating will have the opposite effect in that heating will increase the vapor pressure, and the water vapor will move away from the heated area. Figure 5.31 illustrates these relationships.

The actual amount of water vapor in a soil at optimum moisture for plant growth is surprisingly small, being equivalent to perhaps no more than 10 L of liquid water in the upper 15 cm of a hectare of a silt loam soil. This compares with some 600,000 L of actual liquid water in the same soil volume. Even though the amount of water vapor is small, its movement in soils can be of some practical significance. For example, seeds of some plants can absorb sufficient water vapor from the soil to stimulate germination (see Figure 5.31). Likewise, in dry soils, water vapor movement may be of considerable significance to drought-resistant desert plants (*xerophytes*), many of which can exist at extremely low soil water contents. For instance, at night the surface horizon of a desert soil may cool sufficiently to cause vapor movement up from deeper layers. If cooled enough, the vapor may then condense as dewdrops in the soil pores, supplying certain shallow-rooted xerophytes with water for survival.

5.8 QUALITATIVE DESCRIPTION OF SOIL WETNESS

As an initially water-saturated soil dries down, both the soil as a whole and the soil water it contains undergo a series of gradual changes in physical behavior and in their relationships with plants. These changes are due mainly to the fact that the water remaining in the drying soil is found in smaller pores, in thinner films or in smaller pore corners (review Figure 5.7) where the water potential is lowered principally by the action of matric forces. Matric potential therefore accounts for an increasing proportion of the total soil water potential, while the proportion attributable to gravitational potential decreases.

To study these changes and introduce the terms commonly used to describe varying degrees of soil wetness, we shall follow the moisture and energy status of soil during and after wetting. The terms to be introduced describe various stages along a continuum of soil wetness and should not be interpreted to imply that soil water exists in different "forms." Because these terms are essentially qualitative and lack a precise scientific basis, some soil physicists object to their use. However, it would be a serious disservice to the reader to omit them from

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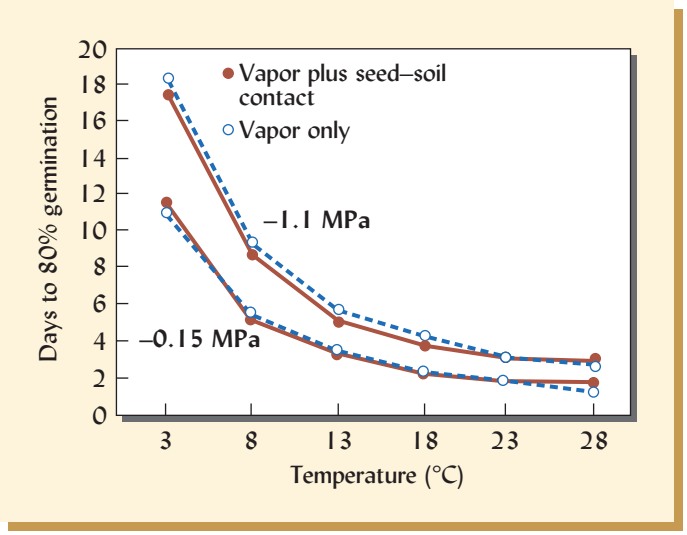

Figure 5.32 *The rate of water vapor movement from nearby soil particles is sufficient to germinate the seeds of wheat as demonstrated in these graphs. In this experiment, either soil is firmly packed around the planted seed (vapor plus seed–soil contact), or the seed is kept from such contact by wrapping it in fiberglass cloth, permitting the movement of only water vapor to the seed (vapor only). Note that where water moves only in the vapor form, seed germination at different temperatures and at two soil water potentials is essentially the same as where there is soil–seed contact.* [(From Wuest et al. (1999))]

this text as they are widely used in practical soil management and help communicate important facts about soil water behavior.

Maximum Retentive Capacity

When all soil pores are filled with water, the soil is said to be *water-saturated* (Figure 5.33) and at its **maximum retentive capacity**. The matric potential is close to zero, nearly the same as that of free water. The volumetric water content is essentially the same as the total porosity. The soil will remain at maximum retentive capacity only so long as water continues to infiltrate, for the water in the largest pores (sometimes termed **gravitational water**) will percolate downward, mainly under the influence of **gravitational forces.** Data on maximum retentive capacities and the average depth of soils in a watershed are useful in predicting how much rainwater can be stored in the soil temporarily, thus possibly avoiding downstream floods.

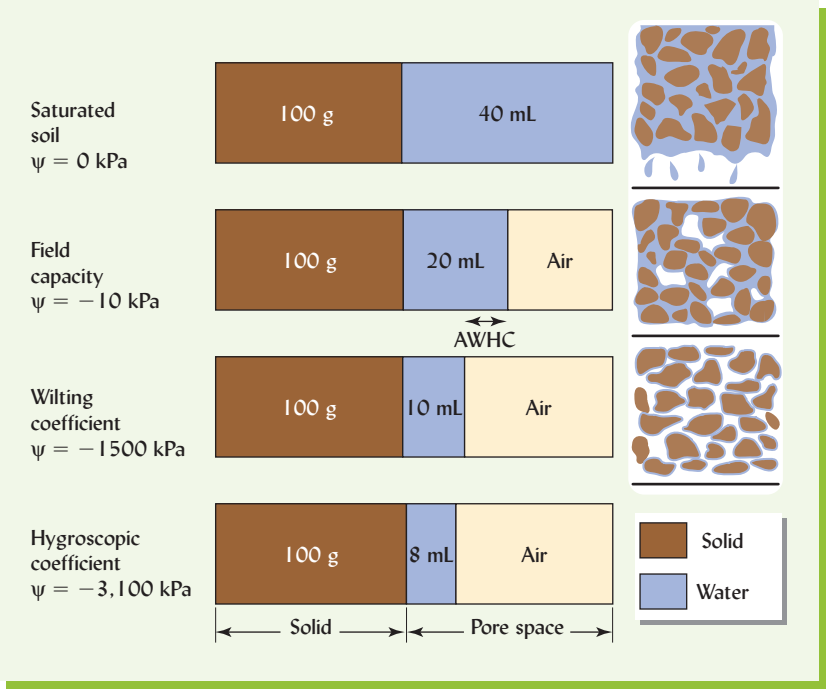

Figure 5.33 *Volumes of water and air associated with 100 g of soil solids in a representative well-granulated silt loam. The top bar shows the situation when the soil is completely saturated with water. This situation will usually occur for short periods of time when water is being added. Water will soon drain out of the larger pores (macropores). The soil is then said to be at field capacity. Plants will remove water from the soil quite rapidly until they begin to wilt. When permanent wilting of the plants occurs, the soil water content is said to be at the wilting coefficient. There is still considerable water in the soil, but it is held too tightly to permit its absorption by plant roots. The water lost between field capacity and wilting coefficient is considered to be the soil's plant available water-holding capacity (AWHC). A further reduction in water content to the hygroscopic coefficient is illustrated in the bottom bar. At this point the water is held very tightly, mostly by the soil colloids.* (Diagram courtesy of Ray R. Weil and N. Brady)

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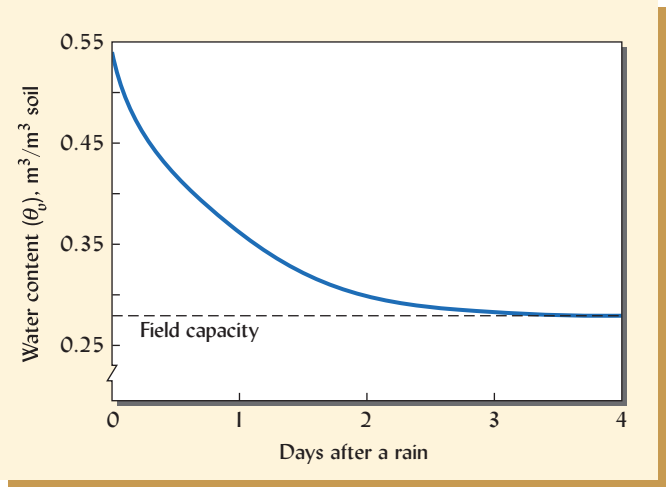

Figure 5.34 *The water content of a soil drops quite rapidly by drainage following a period of saturation by rain or irrigation. After two or three days the rate of water drainage out of the soil is very slow and the soil is said to be at* field capacity. (Diagram courtesy of Ray R. Weil)

Field Capacity

Once the rain or irrigation has ceased, water in the largest soil pores will drain downward quite rapidly in response to the hydraulic gradient (mostly gravity). After one to three days, this rapid downward movement will become negligible as matric forces play a greater role in the movement of the remaining water (Figure 5.34). The soil then is said to be at its **field capacity**. In this condition, water has moved out of the macropores and air has moved in to take its place. The micropores or capillary pores are still filled with water and can supply plants with needed water. The matric potential will vary slightly from soil to soil but is generally in the range of −10 to −30 kPa, assuming drainage into a less-moist zone of similar porosity.[8] Water movement will continue to take place by unsaturated flow, but the rate of movement is very slow since it now is due primarily to capillary forces, which are effective only in micropores (Figures 5.23 and 5.32). The water found in pores small enough to retain it against rapid gravitational drainage, but large enough to allow capillary flow in response to matric potential gradients, is sometimes termed **capillary water**.

While all soil water is affected by gravity, the term *gravitational water* refers to the portion of soil water that readily drains away between the states of maximum retentive capacity and field capacity. Most soil leaching occurs as gravitational water that drains from the larger pores before field capacity is reached. Gravitational water therefore includes much of the water that transports chemicals such as nutrient ions, pesticides, and organic contaminants into the groundwater and, ultimately, into streams and rivers.

Field capacity is a very useful term because it refers to an approximate degree of soil wetness at which several important soil properties are in transition:

1. At field capacity, a soil is holding the maximal amount of water useful to plants. Additional water, while held with low energy of retention, would be of limited use to plants because it would remain in the soil for only a short time before draining, and, while in the soil, it would occupy the larger pores, thereby reducing soil aeration. Drainage of gravitational water from the soil is generally a requisite for optimum plant growth (hydrophilic plants, such as rice or cattails, excepted).
2. At field capacity, the soil is near its lower plastic limit—that is, the soil behaves as a crumbly semisolid at water contents below field capacity, and as a plastic putty-like material that easily turns to mud at water contents above field capacity (see Section 4.9). Therefore, field capacity approximates the upper limit of soil wetness for easy tillage or excavation.
3. At field capacity, sufficient pore space is filled with air to allow optimal aeration for most aerobic microbial activity and for the growth of most plants (see Section 7.6).

[8]Note that because of the relationships pertaining to water movement in stratified soils (see Section 5.6), soil in a flower pot will cease drainage while much wetter than field capacity.

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Permanent Wilting Percentage or Wilting Coefficient

Once an unvegetated soil has drained to its field capacity, further drying is quite slow, especially if the soil surface is covered to reduce evaporation. However, if plants are growing in the soil, they will remove water from their rooting zone, and the soil will continue to dry. The roots will remove water first from the largest water-filled pores where the water potential is relatively high. As these pores are emptied, roots will draw their water from the progressively smaller pores and thinner water films in which the matric water potential is lower and the forces attracting water to the solid surfaces are greater. Hence, it will become progressively more difficult for plants to remove water from the soil at a rate sufficient to meet their needs.

As the soil dries, the rate of plant water removal may fail to keep up with water losses. Plants will then close the openings (**stomata**) in their leaves by which they transpire water and take in carbon dioxide CO_2 for photosynthesis. Plant growth will therefore cease (due to starvation for CO_2) and plant leaves may wilt during the daytime as their cells lose turgor. At first the plants will regain their turgor at night when water is not being lost through the leaves, and the roots can catch up with the plants' demand. Ultimately, however, herbaceous plants will remain wilted night and day when the roots cannot generate water potentials low enough to coax the remaining water from the soil. Woody plants may not wilt *per se*, but their leaves will go flaccid and the water columns in their xylem tissues will be broken and water uptake will be disrupted or cease. Although not yet dead, the plants will soon die if water is not provided. For most annual herbaceous plants this condition develops when the soil water potential ψ has a value of about −1500 kPa (−15 bars). Many trees and a few herbaceous plants, especially xerophytes (desert-type plants) can continue to remove water at even −2000 to −3000 kPa, but the amount of water available between −1500 kPa and −3000 kPa is very small (Figure 5.35).

The water content of the soil at this stage is called the **wilting coefficient** or **permanent wilting percentage** and by convention is taken to be that amount of water retained by the soil when the water potential is −1500 kPa. The soil will appear to be dusty dry, although some water remains in the smallest of the micropores and in very thin films (perhaps only ten molecules thick) around individual soil particles (see Figure 5.33). As illustrated in Figure 5.35, plant **available water** is considered to be that water retained in soils between the states of field capacity and wilting coefficient (conventionally taken to be between −10 kPa and −1500 kPa). The amount of capillary water remaining in the soil that is unavailable to most plants can be substantial in fine-textured soils and those high in organic matter.

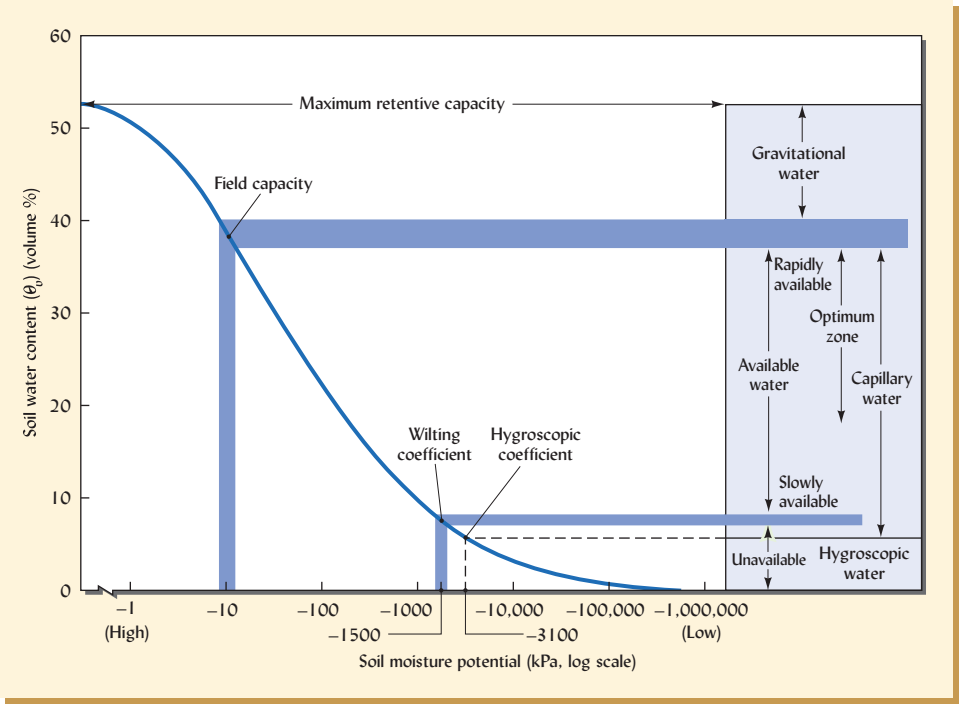

Figure 5.35 *Water content–matric potential curve of a loam soil as related to different terms used to describe water in soils. The shaded bars in the diagram to the right suggest that concepts such as field capacity are only approximations. The gradual change in potential with soil moisture change discourages the concept of different "forms" of water in soils. At the same time, such terms as* gravitational *and* available *assist in the qualitative description of moisture utilization in soils.*

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Table 5.7
VOLUMETRIC WATER CONTENT θ_v AT FIELD CAPACITY, WILTING COEFFICIENT, AND HYGROSCOPIC COEFFICIENT FOR THREE REPRESENTATIVE SOILS AND THE CALCULATED AVAILABLE AND CAPILLARY WATER

Note that the clay soil retains most water at the field capacity, but much of that water is held tightly in the soil at – 3100 kPa potential by soil colloids (hygroscopic coefficient).

	Volume % (θ_v)				
Soil	Field capacity −10 to −30 kPa	Wilting coefficient, −1500 kPa	Hygroscopic coefficient, −3100 kPa	Plant available water, col. 1 – col.2	Capillary water, col. 1 – col. 3
Sandy loam	12	4	3	8	9
Silt loam	30	15	10	15	20
Clay	35	22	18	13	17

Hygroscopic Coefficient

Although plant roots do not generally dry the soil beyond the permanent wilting percentage, if the soil is exposed to the air, water will continue to be lost by evaporation. When soil moisture is lowered below the wilting point, the water molecules that remain are very tightly held, mostly being adsorbed by colloidal soil surfaces. This state is approximated when the atmosphere above a soil sample is nearly saturated with water vapor (98% relative humidity) and equilibrium is established at a water potential of −3100 kPa. The water is thought to be in films only four or five molecules thick and is held so rigidly that much of it is considered nonliquid and can move only in the vapor phase. The moisture content of the soil at this point is termed the **hygroscopic coefficient**. Soils high in colloidal materials (clay and humus) will hold more water under these conditions than will sandy soils that are low in clay and humus (Table 5.7). Soil water considered to be *unavailable* to plants includes the hygroscopic water as well as that portion of capillary water retained at potentials below −1500 kPa (see Figure 5.35).

5.9 FACTORS AFFECTING AMOUNT OF PLANT-AVAILABLE SOIL WATER

The amount of soil water available for plant uptake is determined by a number of factors, including the relationship between water content and water potential for each soil horizon, soil strength and density effects on root growth, soil depth, rooting depth, and soil stratification or layering. Each will be discussed briefly.

Water Content–Potential Relationship

As illustrated in Figure 5.35, there is a relationship between the water potential of a given soil and the amount of water held at field capacity and at permanent wilting percentage, the two boundary properties determining the available water-holding capacity. This energy-controlling concept should be kept in mind as we consider the various soil properties that affect the amount of water a soil can hold for plant use.

The general influence of texture on field capacity, wilting coefficient, and **available water-holding capacity** is shown in Figure 5.36. Note that as fineness of texture increases, there is a general increase in available moisture storage from sands to loams and silt loams. Plants growing on sandy soils are more apt to suffer from drought than are those growing on a silt loam in the same area (see Figure 5.37). However, clay soils frequently provide less available water than do well-granulated silt loams since the clays tend to have a high wilting coefficient.

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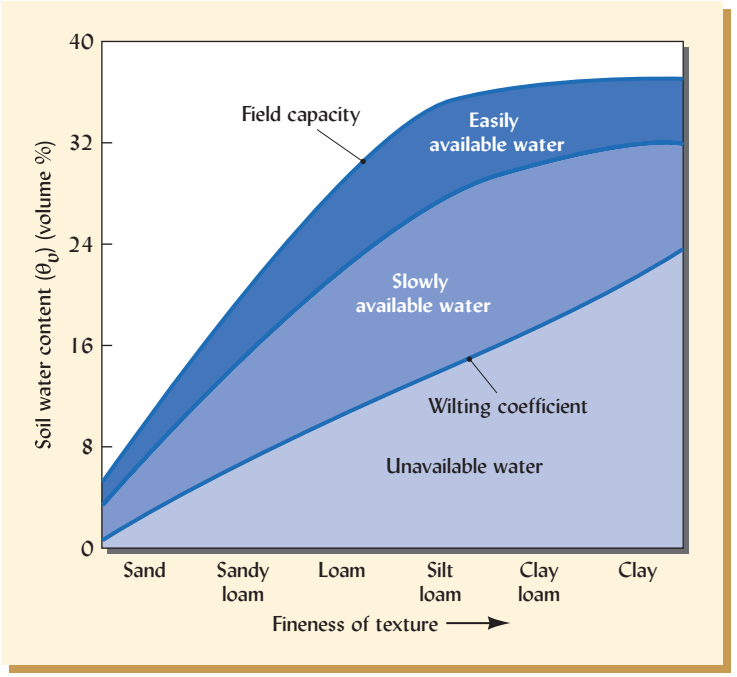

Figure 5.36 *General relationship between soil water characteristics and soil texture. Note that the wilting coefficient increases as the texture becomes finer. The field capacity increases until we reach the silt loams, then levels off. Remember these are representative curves; individual soils would probably have values different from those shown.* (Diagram courtesy of Ray R. Weil and N. Brady)

Soil organic matter exerts both direct and indirect influences that contribute increased soil water availability. The direct effects are due to the very high volumetric water-holding capacity of organic matter, which, when the soil is at the field capacity, is much higher than that of an equal volume of mineral matter (see curve for peat soil in Figure 5.12). Even though the water held by organic matter at the wilting point is also somewhat higher than that held by mineral matter, the amount of water available for plant uptake is still greater from the organic fraction. Figure 5.38 provides data from a series of experiments to justify this conclusion.

Organic matter indirectly affects the amount of water available to plants mainly by enhancing soil structure (see Section 4.5), which in turn increases both water infiltration and water-holding capacity. Recognition of the beneficial effects of organic matter on plant-available water is essential for wise soil management.

Compaction Effects on Matric Potential, Aeration, and Root Growth

Soil compaction generally reduces the amount of water that plants can take up. Four factors account for this negative effect. First, compaction crushes many of the macropores and large

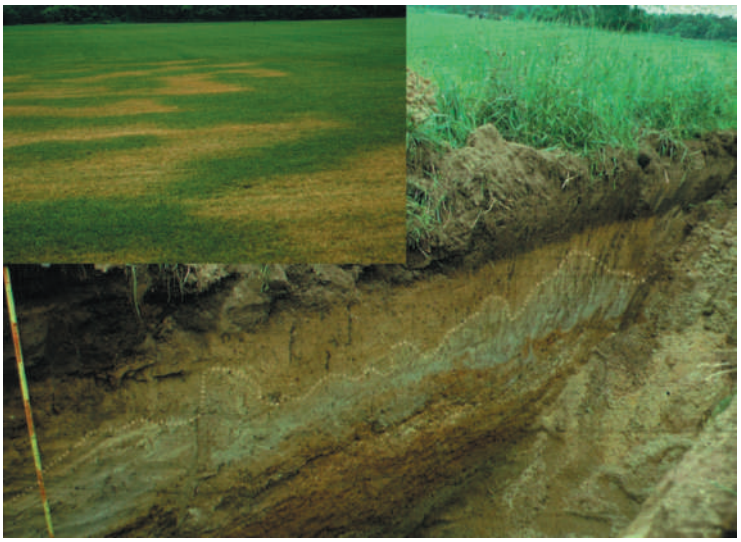

Figure 5.37 *An unusual spatial pattern of drought stress in turfgrass* (inset) *reflects the influence of soil texture and depth on plant-available water holding capacity. As can be seen in the wall of the excavated trench, an uneven silt mantle is layered on top of glacially deposited sands and gravels in this Rhode Island, USA, Inceptisol. The boundary between the silty mantle and the underlying coarse material is highlighted by a thin dashed line. Where the silty layer is thick, the profile has a greater water holding capacity and the turfgrass remained green during a prolonged period of hot, dry weather.* (Photos courtesy of Ray R. Weil)

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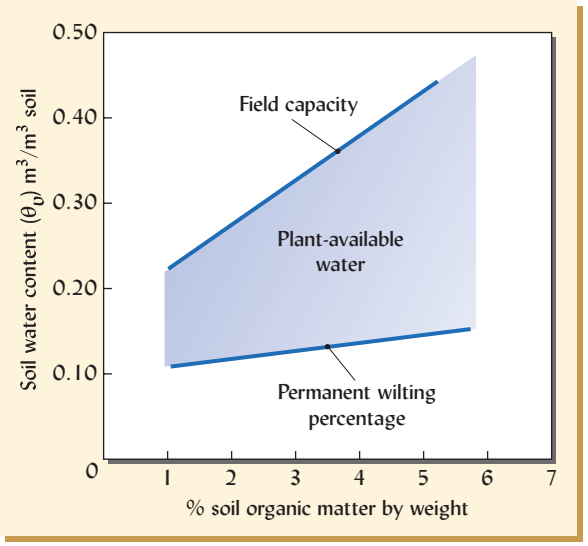

Figure 5.38 *The effects of organic matter content on the field capacity and permanent wilting percentage of a large number of silt loam soils. The difference between the two lines shown is the available soil moisture content, which was obviously greater in the soils with higher organic matter levels.* [Redrawn from Hudson (1994); used with permission of the Soil & Water Conservation Society]

micropores into smaller pores, and the bulk density increases. As the clay particles are forced closer together, soil strength may increase beyond about 2000 kPa, the level considered to limit root penetration. Second, compaction decreases the total pore space, which generally means that less water is retained at field capacity. Third, reduction in macropore size and numbers generally means less air-filled pore space when the soil is near field capacity. Fourth, the creation of more very fine micropores will increase the permanent wilting coefficient and so decrease the available water content.

Least Limiting Water Range. These four factors associated with soil compaction are integrated in Figure 5.39, which compares two different concepts of water availability to roots. The figure illustrates the effect of compaction (bulk density) on the range of soil water contents defining **plant-available water** and the **least limiting water range.** We have already defined plant-available water as that held with matric potentials between field capacity (−10 to −30 kPa) and the permanent wilting point (−1500 kPa). Thus, plant-available water is that which is not held too tightly for roots to take up and yet is not held so loosely that it freely drains away by gravity. The least limiting water range is that range of water contents for which soil conditions do not severely restrict root growth.

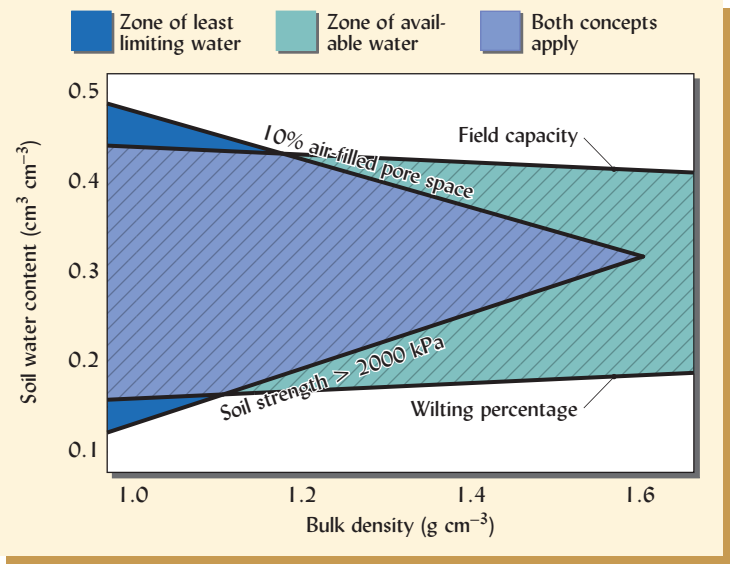

Figure 5.39 *Influence of increased bulk density on the range of soil water contents available for plant uptake. Traditionally, plant-available water is defined as that retained between field capacity and wilting percentage (vertical hatching). If soils are compacted, however, plant use of water may be restricted by poor aeration (<10% air-filled pore space) at high water contents and by soil strength (>2000 kPa) that restricts root penetration at low water contents. The latter criteria define the* least limiting water range *shown by horizontal hatching. The two sets of boundary criteria give similar results when the soil is not compacted (bulk density is about 1.25 for the soil illustrated).* [Drawn from concepts in from Da Silva and Kay (1997)]

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Oxygen Supply in Wet Soil. According to the least limiting water range concept, soils are too *wet* for normal root growth when so much of the soil pore space is filled with water that less than about 10% remains filled with air. At this water content, lack of oxygen for respiration limits root growth. In loose, well-aggregated soils, this water content corresponds quite closely to field capacity. However, in a compacted soil with very few large pores, oxygen supply may become limiting at lower water contents (and potentials) because some of the smaller pores will be needed for air.

Soil Strength in Dry Soil. The least limiting water range concept tells us that soils are too *dry* for normal root growth when the soil strength (measured as the pressure required to push a pointed rod through the soil) exceeds about 2000 kPa. This level of soil strength occurs at water contents near the wilting point in loose, well-aggregated soils, but may occur at considerably higher water contents if the soil is compacted (see Figure 5.40). To summarize, the least limiting water range concept suggests that root growth is limited by lack of oxygen at the wet end of the range and by the inability of roots to physically push through the soil at the dry end. Thus, compaction effects on root growth are greatest in dry soils (Figure 5.41).

Osmotic Potential

The presence of soluble salts, either from applied fertilizers or as naturally occurring compounds, can influence plant uptake of soil water. For soils high in salts, the osmotic potential ψ_o of the soil solution will contribute to the total moisture stress along with the matric potential. The osmotic potential tends to reduce available moisture in such soils because more water is retained in the soil at the permanent wilting coefficient than would be the case due to matric potential alone. In most humid-region soils these osmotic potential effects are insignificant, but they become of considerable importance for certain soils in dry regions that may accumulate soluble salts through irrigation or natural processes (see Section 10.2).

Soil Depth and Layering

Our discussion thus far has referred to available water-holding capacity as the percentage of the soil volume consisting of pores that can retain water at potentials between field capacity and wilting percentage. The total volume of available water will depend

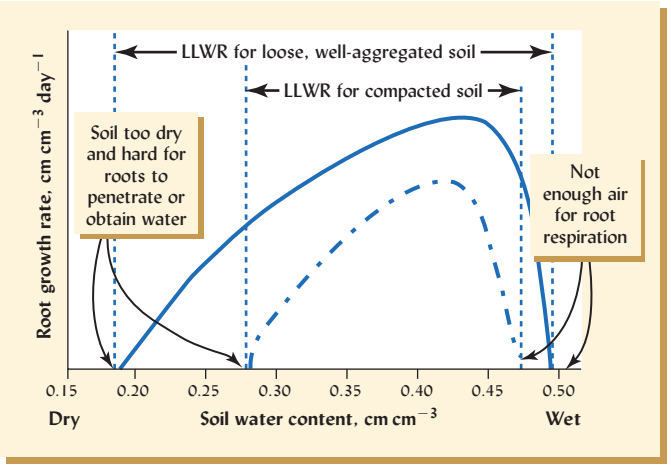

Figure 5.40 *Compaction (dashed curve) reduces the range of soil water contents suitable for root growth, thus narrowing the least limiting water range.* (Diagram courtesy of Ray R. Weil)

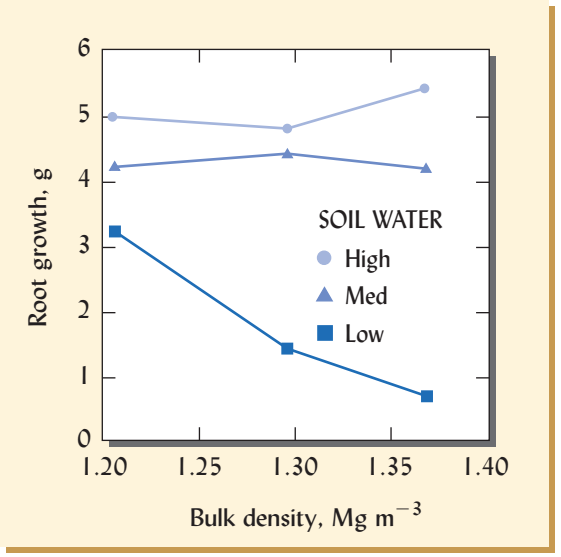

Figure 5.41 *Root growth of Lodgepole pine seedlings in response to increased compaction at three soil water levels. Compaction affected root growth only when soil water was low, probably because root growth was limited by high soil strength. The tree seedlings were grown in pots of mineral soil compacted to three bulk density levels.* (Drawn from data in Blouin et al. [2004])

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on the total volume of soil explored by plant roots. This volume may be governed by the total depth of soil above root-restricting layers, by the greatest rooting depth characteristic of a particular plant species, or even by the size of a pot chosen for containerized plants. The depth of soil available for root exploration is of particular significance for deep-rooted plants (see Figure 1.4), especially in subhumid to arid regions where perennial vegetation depends on water stored in the soils for survival during long periods without precipitation.

Soil stratification or layering can markedly influence the available water and its movement in the soil. Impervious layers drastically slow down the rate of water movement and also restrict the penetration of plant roots, thereby reducing the soil depth from which moisture is drawn. Sandy layers also act as barriers to soil moisture movement from the finer-textured layers above, as explained in Section 5.6.

The capacity of soils to store available water determines to a great extent their usefulness for plant growth (see Figures 5.42 and 5.43). This capacity provides a buffer between

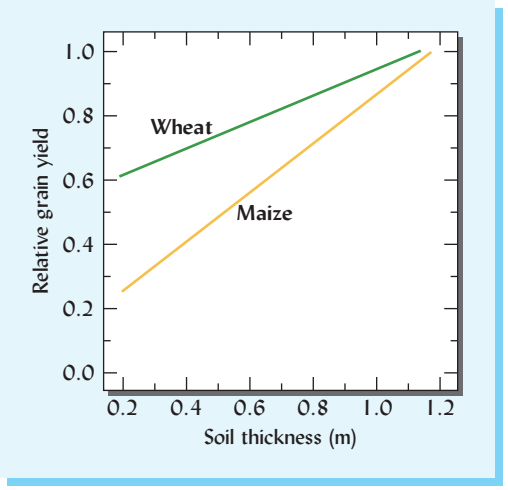

Figure 5.42 *Relative grain yields for maize and wheat in relation to thickness of soil available for rooting. The crops were all grown with no-till management in Argiudolls and Paleudolls of the southeastern Pampas in Argentina. These soils held about 1.5 mm of available water per 1 cm of soil depth. Maize, which was grown during the hot, dry weather from spring to fall, was much more responsive to increased soil thickness than winter wheat, which was grown during the cooler, low water–demand period from fall to spring. In this case the soil thickness was limited by a root-restricting petrocalcic (cemented) horizon.* [Drawn from data in Sadras and Calvino (2001)]

Figure 5.43 *Soil depth and competition for soil water between trees and turfgrass in lawn landscapes during an extended period of hot, dry weather.* (Left) *The brown, drought-stressed grass near the line of trees shows where tree roots have used most of the available water in the topsoil some 10–15 m beyond the tree canopy itself. The trees have an advantage in competing for water partly because water uptake by their roots is driven by the large canopy leaf area.* (Right) *In this scene, with the greenest grass nearest the trees, the pattern of drought stress in the grass appears to be opposite from that in the scene on the left. What accounts for the difference? The rectangular area of brown grass is actually a green roof atop a below-ground building. The soil on this vegetated roof is less than 20 cm thick and so has been depleted of it's total profile store of available water. The trees are planted beyond the edge of the green roof in native soil where both the grass and the tree roots can exploit the much larger total available water supply held by a deeper soil profile.* (Photos courtesy of Ray R. Weil)

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an adverse climate and plant production. The productivity of forest sites is often related to soil water-holding capacity. In irrigated soils, it helps determine the frequency with which water must be applied. Soil water-holding capacity is becoming increasingly important for global ecosystem management as the use of water for all purposes—industrial and domestic, as well as irrigation—begins to tax the supply of this critical natural resource. To estimate the water-holding capacity of a soil, each soil horizon to which roots have access may be considered separately and then summed to give the total water-holding capacity for the profile (see Box 5.4).

BOX 5.4

TOTAL AVAILABLE WATER-HOLDING CAPACITY OF A SOIL PROFILE

The total amount of water available to a plant growing in a field soil can be estimated from the rooting depth of the plant and the amount of water held between field capacity and wilting percentage in each of the soil horizons explored by the roots. For each soil horizon, the mass available water-holding capacity (AWHC) is estimated as the difference between the mass water content at field capacity θ_{mFC} (g water per 100 g soil at field capacity) and that at permanent wilting percentage, θ_{mWP}. This value can be converted into a volume water content θ_v by multiplying by the ratio of the bulk density D_b of the soil to the density of water D_w. Finally, this volume ratio is multiplied by the thickness of the horizon to give the total centimeters of available water capacity *AWHC* in that horizon.

$$AWHC = (\theta_{mFC} - \theta_{mWP}) \times D_b \times D_w \times L \qquad (5.11)$$

For the first horizon described in Table 5.8 we can substitute values (with units) into Eq. (5.11):

$$AWHC = \left(\frac{22\text{ g}}{100\text{ g}} - \frac{8\text{ g}}{100\text{ g}}\right) \times \frac{1.2\text{ Mg}}{\text{m}^3} \times \frac{1\text{ m}^3}{1\text{ Mg}} \times 20\text{ cm}$$

$$= 3.36\text{ cm}$$

Note that all units cancel out except cm, resulting in the depth of available water (cm) held by the horizon. In Table 5.8 the *AWHC* of all horizons within the rooting zone are summed to give a total *AWHC* for the soil–plant system. Since no roots penetrated to the last horizon (1.0 to –1.25 m), this horizon was not included in the calculation. We can conclude that for the soil–plant system illustrated, 14.13 cm of water could be stored for plant use. At a typical warm weather water-use rate of 0.5 cm of water per day, this soil could hold about a four-week supply.

Table 5.8
CALCULATION OF ESTIMATED SOIL PROFILE AVAILABLE WATER-HOLDING CAPACITY (AWHC)

Soil depth, cm	Relative root length	Soil depth increment, cm	Soil bulk density, Mg/m^3	Field capacity (FC), g/100 g	Wilting percentage (WP), g/100 g	AWHC, cm
0–20	xxxxxxxxx	20	1.2	22	8	$20 \times 1.2\left(\frac{22}{100} - \frac{8}{100}\right) = 3.36$ cm
20–40	xxxx	20	1.4	16	7	$20 \times 1.4\left(\frac{16}{100} - \frac{7}{100}\right) = 2.52$ cm
40–75	xx	35	1.5	20	10	$35 \times 1.5\left(\frac{20}{100} - \frac{10}{100}\right) = 5.25$ cm
75–100	xx	25	1.5	18	10	$25 \times 1.5\left(\frac{18}{100} - \frac{10}{100}\right) = 3.00$ cm
100–125	—	25	1.6	15	11	No roots
Total						3.36 + 2.52 + 5.25 + 3.00 = 14.13 cm

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5.10 MECHANISMS BY WHICH PLANTS ARE SUPPLIED WITH WATER

At any one time, only a small proportion of the soil water is adjacent to absorptive plant–root surfaces. How then do the roots get access to the immense amount of water (see Section 6.3) needed by vigorously growing plants? Two phenomena seem to account for this access: the capillary movement of the soil water to plant roots and the growth of the roots into moist soil.

Rate of Capillary Movement

When plant rootlets absorb water, they reduce the water content in the soil immediately surrounding them. Thus, roots set up a water potential gradient that causes water to move from the more moist, higher potential bulk soil toward the drier, lower potential soil adjacent to the roots. The rate of movement depends on the magnitude of the potential gradients developed and the conductivity of the soil pores. With some sandy soils, the adjustment may be comparatively rapid and the flow appreciable if the soil is near field capacity. In fine-textured and poorly granulated clays, the movement will be sluggish and only a meager amount of water will be delivered. However, in drier conditions with water held at lower potentials, a clay soil will eventually be able to deliver more water by capillarity than a sandy soil because the latter will have very few capillary pores still filled with water.

The total distance that water flows by capillarity on a day-to-day basis may be only a few centimeters. This might suggest that capillary movement is not a significant means of enhancing moisture uptake by plants. However, if the roots have penetrated much of the soil volume so that individual roots are rarely more than a few centimeters apart, movement over greater distances may not be necessary. Even during periods of hot, dry weather when evaporative demand is high, capillary movement can be an important means of providing water to plants. It is of special significance during periods of low moisture content when plant root extension is low.

Rate of Root Extension

Capillary movement of water is complemented by rapid rates of root extension, which ensure that new root–soil contacts are constantly being established. Such root penetration may be rapid enough to take care of most of the water needs of a plant growing in a soil at optimum moisture. The mats of roots, rootlets, and root hairs in a forest floor or a meadow sod exemplify successful adaptations of terrestrial plants for exploitation of soil water storage.

The primary limitation of root extension is the small proportion of the soil with which roots are in contact at any one time. Even though the root surface is considerable, root–soil contacts commonly account for less than 1% of the total soil surface area. This suggests that most of the water must move from the soil to the root even though the distance of movement may be no more than a few millimeters. It also suggests the complementarity of capillarity and root extension as means of providing soil water for plants.

Root Distribution

The distribution of roots in the soil profile determines to a considerable degree the plant's ability to absorb soil water. Most plants, both annuals and perennials, have the bulk of their roots in the upper 25–30 cm of the profile. For most plants in limited rainfall regions, roots explore relatively deep soil layers, but usually 95% of the entire root system is contained in the upper 2 m of soils. As Figure 5.44 shows, in more humid regions rooting tends to be somewhat shallower. Perennial plants, both woody and herbaceous, produce some roots that grow very deeply (>3 m) and are able to absorb a considerable proportion of their moisture

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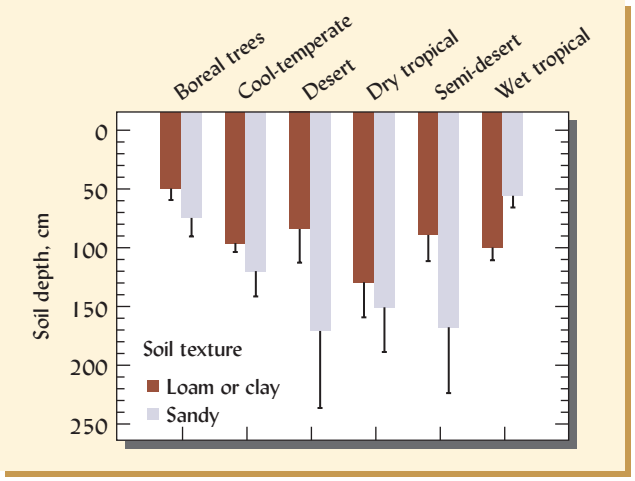

Figure 5.44 *The soil depth above which 95% of all roots are located under different vegetation and soil types. The analysis used 475 root profiles reported from 209 geographic locations. The deepest rooting depths were found mainly in water-limited ecosystems. Within all but the wettest ecosystem, rooting was deeper in the sandier soils. Globally, 9 out of 10 profiles had at least 50% of all roots in the upper 30 cm of the soil profile and 95% of all roots in the upper 2 m (including any O horizons present).* [Redrawn from Schenk and Jackson (2002)]

from deep subsoil layers. Even in these cases, however, it is likely that much of the root absorption is from the upper layers of the soil, provided these layers are well supplied with water. On the other hand, if the upper soil layers are moisture-deficient, even annual row crops such as sunflower, corn, and soybeans will absorb much of their water from the lower horizons (Figure 5.45), provided that adverse physical or chemical conditions do not inhibit their exploration of these horizons.

Root–Soil Contact

As roots grow into the soil, they move into pores of sufficient size to accommodate them. Contact between the outer cells of the root and the soil permits ready movement of water from the soil into the plant in response to differences in energy levels (Figure 5.46). When the plant is under moisture stress, however, the roots tend to shrink in size as their cortical cells lose water in response to this stress. Such conditions exist during hot, dry weather and are most severe during the daytime, when water loss through plant leaves is at a maximum. The diameter of roots under these conditions may shrink by 30%. This reduces the direct root–soil contact considerably, as well as the movement of liquid water and nutrients into the plants. While water vapor can still be absorbed by the plant, its rate of absorption is too low to keep any but the most drought-tolerant plants alive.

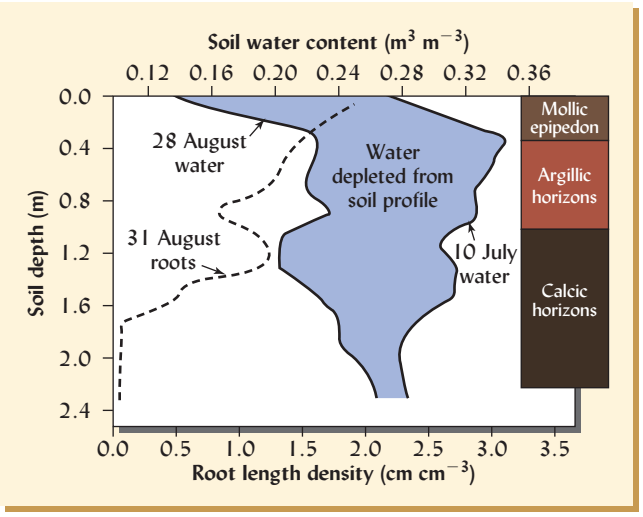

Figure 5.45 *Distribution of roots and depletion of water in the profile of a soil growing sunflowers under dryland conditions in Texas, USA. Notice the relationship between root density (cm of root length per cm^3 of soil) and amount of water used during the hot, dry weather between 10 July and 28 August. The water content on 28 August is near the wilting point in the upper 1 m of this Pullman clay loam (Torrertic Paleustolls).* [Drawn from data in Moroke et al. (2005)]

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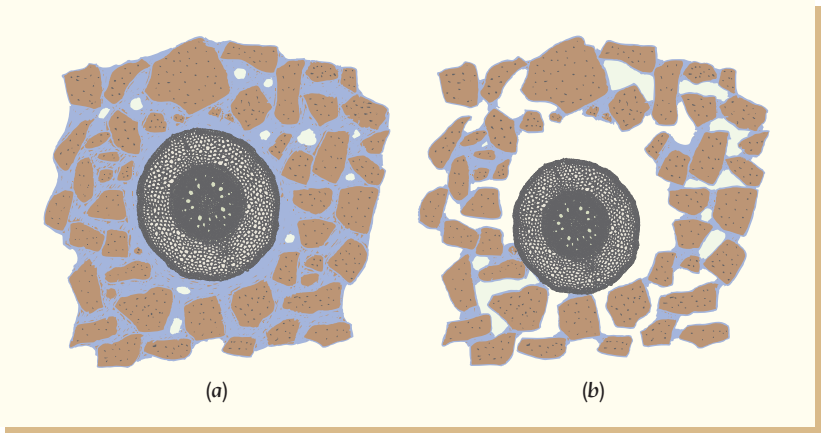

Figure 5.46 *Cross-section of a root surrounded by soil.* (a) *During periods of adequate moisture and low plant moisture stress, the root completely fills the soil pores and is in close contact with the soil water films.* (b) *When the plant is under severe moisture stress, such as during hot, dry weather, the root shrinks (mainly in the cortical cells), significantly reducing root–soil contact. Such root shrinkage can occur on a hot day even if soil water content is high.* [Diagram courtesy of Ray R. Weil, based on concepts in Huck et al. (1970)]

5.11 CONCLUSION

Water impacts all life. The interactions and movement of this simple compound in soils help determine whether these impacts are positive or negative. An understanding of the principles that govern the attraction of water for soil solids and for dissolved ions can help land managers maximize the positive impacts while minimizing the less desirable ones.

The water molecule has a polar structure that results in electrostatic attraction of water to both soluble cations and soil solids. These attractive forces tend to reduce the potential energy level of soil water below that of pure water. The extent of this reduction, called soil water potential ψ, has a profound influence on a number of soil properties, but especially on the movement of soil water and its uptake by plants.

The water potential due to the attraction between soil solids and water (the matric potential ψ_m) combines with the force of gravity ψ_g to largely control water movement. This movement is relatively rapid in soils high in moisture and with an abundance of macropores. In drier soils, however, the adsorption of water on the soil solids is so strong that its movement in the soil and its uptake by plants are greatly reduced. As a consequence, plants can die for lack of water—even though there are still significant quantities of water in the soil—because that water is unavailable to plants.

Water is supplied to plants by capillary movement toward the root surfaces and by growth of the roots into moist soil areas. In addition, vapor movement may be of significance in supplying water for drought-resistant desert species (xerophytes). The osmotic potential ψ_o becomes important in soils with high soluble salt levels that can impede plant uptake of water from the soil. Such conditions occur most often in soils with restricted drainage in areas of low rainfall, in irrigated soils, and in potted indoor plants.

The characteristics and behavior of soil water are quite complex. As we have gained more knowledge, however, it has become apparent that soil water is governed by relatively simple, basic physical principles. Furthermore, researchers are discovering the similarity between these principles and those governing the movement of groundwater and the uptake and use of soil moisture by plants—the subject of the next chapter.

STUDY QUESTIONS

1. What is the role of the *reference state of water* in defining soil water potential? Describe the properties of this reference state of water.
2. Imagine a root of a cotton plant growing in the upper horizon of an irrigated soil in California's Imperial Valley. As the root attempts to draw water molecules from this soil, what forces (potentials) must it overcome? If this soil were compacted by a heavy vehicle, which of these forces would be most affected? Explain.
3. Using the terms *adhesion, cohesion, meniscus, surface tension, atmospheric pressure*, and *hydrophilic surface*, write a brief essay to explain why water rises up from the water table in a mineral soil.

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4. Suppose you were hired to design an automatic irrigating system for a wealthy homeowner's garden. You determine that the flower beds should be kept at a water potential above −60 kPa, but not wetter than −10 kPa, as the annual flowers here are sensitive to both drought and lack of good aeration. The rough turf areas, however, can do well if the soil dries to as low as −300 kPa. Your budget allows either tensiometers or electrical resistance blocks to be hooked up to electronic switching valves. Which instruments would you use and where? Explain.
5. Suppose the homeowner referred to in question 4 increased your budget and asked to use the capacitance method to measure soil water contents. What additional information about the soils, not necessary for using the tensiometer, would you have to obtain to use the capacitance instrument to meet the criteria stated in question 4? Explain.
6. A greenhouse operator was growing ornamental woody plants in 15-cm-tall plastic containers filled with a loamy sand. He watered the containers daily with a sprinkler system. His first batch of 1000 plants yellowed and died from too much water and not enough air. As an employee of the greenhouse, you suggest that he use 30-cm-tall pots for the next batch of plants. Explain your reasoning.
7. Suppose you measured the following data for a soil:

		θ_m at different water tensions, kg water/kg dry soil		
Horizon	Bulk density, Mg/m^3	−10 kPa	−100 kPa	−1500 kPa
A (0–30 cm)	1.28	0.28	0.20	0.08
Bt (30–70 cm)	1.40	0.30	0.25	0.15
Bx (70–120 cm)	1.95	0.20	0.15	0.05

Estimate the total available water-holding capacity (AWHC) of this soil in centimeters of water.

8. A forester obtained a cylindrical ($L = 15$ cm, $r = 3.25$ cm) core of soil from a field site. She placed all the soil in a metal can with a tight-fitting lid. The empty metal can weighed 300 g and when filled with the field-moist soil weighed 972 g. Back in the lab, she placed the can of soil, with lid removed, in an oven for several days until it ceased to lose weight. The weight of the dried can with soil (including the lid) was 870 g. Calculate both θ_m and θ_v.
9. Give four reasons why compacting a soil is likely to reduce the amount of water available to growing plants.
10. Since even rapidly growing, finely branched root systems rarely contact more than 1 or 2% of the soil particle surfaces, how is it that the roots can utilize much more than 1 or 2% of the water held on these surfaces?
11. For two soils subjected to "no," "moderate," or "severe" compaction, Figure 5.15 shows the volume fraction (cm^3/cm^3) of pores in three size classes. The symbol ◀ indicates the volume fraction of water, θ_v (cm^3/cm^3), in each soil. The figure indicates that $\theta_v \approx 0.35$ for the uncompacted clay loam (bulk density = 0.75 g/cm^3). Show a complete calculation (with all units) to demonstrate that ◀ in the figure correctly indicates that $\theta_v \approx 0.36$ for the severely compacted sandy loam (bulk density = 1.10 g/cm^3).
12. Saturated flow is one of three types of water movement in soils. Infiltration of water into an irrigated furrow is one example of this type of water flow. Name the other two types of water flow in soils and for each type, briefly describe three real-world examples.
13. Fill in the shaded cells of this table to show the cm of available water capacity in the entire 90 cm profile. Show complete calculations for the first (upper left) and last (lower right) of the shaded cells.

		Field capacity		Wilting point		Available water	
Soil depth, cm	Bulk density, D_b, (Mg/m^3)	θ_m, [a]%	θ_d, [b]cm	θ_m, %	θ_d, cm	θ_m, %	θ_d, cm
0–30	1.48	27.1	_____	17.9	_____	9.2	_____
30–60	1.51	27.5	_____	18.1	_____	9.4	_____
60–90	1.55	27.1	_____	20.0	_____	7.1	_____
0–90	—	—	_____	—	_____	—	_____

[a]θ_m is water content by mass and is reported here as percent (%), which is equivalent to g water/100 g dry soil.
[b]θ_d is water content by depth and is reported a mm of water held in the soil layer indicated.

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REFERENCES

Bartlett, M. K., C. Scoffoni, and L. Sack. 2012. "The determinants of leaf turgor loss point and prediction of drought tolerance of species and biomes: A global meta-analysis." *Ecology Letters* **15**:393–405.

Blouin, V., M. Schmidt, C. Bulmer, and M. Krzic. 2004. "Soil compaction and water content effects on lodgepole pine seedling growth in British Columbia." In B. Singh (ed.). *Supersoil 2004*. Program and Abstracts for the 3rd Australian-New Zealand Soils Conference. University of Sydney, Sydney, Australia. http://www.regional.org.au/au/asssi/supersoil2004/s14/oral/2036_blouinv.htm.

Cameira, M. R., R. M. Fernando, and L. S. Pereira. 2003. "Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal." *Soil Tillage Research* **70**:131–140.

Carter, L. J., and T. H. Pigford. 2005. "Proof of safety at Yucca Mountain." *Science* **310**:447–448.

Cooney, J. J., and J. E. Peterson. 1955. *Avocado irrigation*. Leaflet 50. California Agricultural Extension Service. Davis, CA.

Da Silva, A. P., and B. D. Kay. 1997. "Estimating the least limiting water range of soil from properties and management." *Soil Science Society of America Journal* **61**:877–883.

Hillel, D. 2004. *Introduction to environmental soil physics*. Elsevier Science, New York. p. 494.

Huck, M. G., B. Klepper, and H. M. Taylor. 1970. "Diurnal variations in root diameter." *Plant Physiology* 45:529.

Hudson, B. D. 1994. "Soil organic matter and available water capacity." *Journal of Soil and Water Conservation* **49**:189–194.

Kladivko, E. J., et al. 1999. "Pesticide and nitrate transport into subsurface tile drains of different spacing." *Journal of Environmental Quality* **28**:997–1004.

Moroke, T. S., R. C. Schwartz, K. W. Brown, and A. S. R. Juo. 2005. "Soil water depletion and root distribution of three dryland crops." *Soil Science Society of America Journal* **69**:197–205.

Rawls, W. J., D. L. Brakensiek, and K. E. Saxton. 1982. "Estimation of soil water properties." *Transactions of the ASAE* **25**:1316–1320, 1328.

Rawls, W. J., A. Nemes, Y. Pachepsky, Y. Pachepsky, and W. J. Rawls. 2004. "Effect of soil organic carbon on soil hydraulic properties." *Developments in soil science*. Elsevier. Vol. 30, pp. 95–114. New York.

Richards, L. A. 1965. "Physical condition of water in soil." *Agronomy 9: Methods of Soil Analysis, Part 1*. American Society of Agronomy, Madison, WI.

Sadras, V. O., and O. A. Calvino. 2001. "Quantification of grain yield response to soil depth in soybean, maize, sunflower and wheat," *Agronomy Journal* **93**:577–583.

Schenk, H., and R. Jackson. 2002. "The global biogeography of roots," *Ecological Monographs* **72**:311–328.

Schwärzel, K., M. Renger, R. Sauerbrey, and G. Wessolek. 2002. "Soil physical characteristics of peat soils." *Journal of Plant Nutrition and Soil Science* **165**:479–486.

Shestak, C. J., and M. D. Busse. 2005. "Compaction alters physical but not biological indices of soil health," *Soil Science Society of America Journal* **69**:236–246.

Waddell, J. T., and R. R. Weil. 1996. "Water distribution in soil under ridge-till and no-till corn," *Soil Science Society of America Journal* **60**:230–237.

Warrick, A. W. 2001. *Soil physics companion*. CRC Press, Boca Raton, FL. p. 400.

Wuest, S. B., S. L. Albrecht, and K. W. Skirvin. 1999. "Vapor transport vs. seed–soil contact in wheat germination," *Agronomy Journal* **91**:783–787.

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Water cycles from soil to clouds and back in the Teton Mountains. (Ray R. Weil)

6 Soil and the Hydrologic Cycle

Both soil and water belong to the biosphere, to the order of nature, and—as one species among many, as one generation among many yet to come—we have no right to destroy them.
—*Daniel Hillel*, Out of Earth

One of the most striking—and troubling—features of human society is the yawning gap in wealth between the world's rich and poor. The life experience of the one group is quite incomprehensible to the other. So it is with the distribution of the world's water resources. The rain forests of the Amazon and Congo basins are drenched by more than 2000 mm of rain each year, while the deserts of North Africa and central Asia get by with less than 200. South America and the Caribbean receive nearly one-third of the annual global precipitation, Australia only 1%. Nor is the supply of water distributed evenly throughout the year. Rather, periods of high rainfall and flooding alternate with dry spells or periods of drought.

Yet one could say that everywhere the supply of water is adequate to meet the needs of the plants and animals native to the natural communities of the area. Of course, this is so only because the plants and animals have adapted to the local availability of water. Early human populations, too, adapted to the local water supplies by settling where water was plentiful from rain or rivers, by learning which gourds and plant stems could quench one's thirst, by developing techniques to harvest water for agriculture and store it in underground cisterns, and by adopting nomadic lifestyles that allowed them and their herds to follow the rains and the grass supply.

But "civilized" humans have not been willing to adapt their needs and cultures to their environment. Rather, they have joined in organized efforts to adapt their environment to their desires. Hence, the ancients tamed the flows of the Tigris and Euphrates. We moderns dig wells in the Sahel, bottle up the mighty Nile at Aswan, channel the waters of the Colorado to the chaparral region of southern California in the United States, pump out the aquifers under farms and suburbs, and create sprawling cities (with swimming pools and bluegrass lawns!) in the deserts of the American Southwest or on the sands of Arabia.

There is plenty of room for improvement in managing water resources, and many of the improvements are likely to come as a result of better management of soils. The soil plays a central role in the cycling and use of water. For instance, by serving as a massive reservoir, soil helps moderate the adverse effects of excesses and deficiencies of water. It takes in water during times of surplus and then releases it in due time, either to satisfy the transpiration (T) requirements of plants or to replenish groundwater. Stable structure at the surface of the soil ensures that a large fraction of the precipitation received will move slowly into the groundwater and from there to nearby streams or to deeper reservoirs under the earth. The soil can help us purify and reuse wastewaters from animal, domestic, and

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industrial sources. The flow of water through the soil in these and other circumstances connects the chemical pollution of soils to the possible contamination of groundwater.

In Chapter 5 we considered the nature and movement of water in soils. In this chapter we will see how those characteristics apply to the management of water as it cycles between the soil, the atmosphere, and vegetation. We will then examine the unique role of the soil in water-resource management.

6.1 THE GLOBAL HYDROLOGIC CYCLE

Global Stocks of Water

There are nearly 1400 million km^3 of water on Earth—enough (if it were all aboveground at a uniform depth) to cover the Earth's surface to a depth of some 3 km. Most of this water, however, is saline and/or inaccessible and is not active in the annual cycling of water that supplies rivers, lakes, and living things. Almost 97% is found in oceans (Figure 6.1) where the water is not only salty, but has an average **residence time** of several thousand years. Only the near-surface ocean layers take part in annual water cycling. An additional 1.7% of the water is in glaciers and ice caps of mountains with similarly long residence times (about 10,000 years). Some 1.7% is found in groundwater, most of which is more than 750 m underground and about half of which is saline. Except where it is pumped by humans, it, too, has a long average residence time measured in centuries.

The water with shorter residence times (that which cycles more actively) is in the surface layer of the oceans, in shallow groundwater, in lakes and rivers, in the atmosphere, and in the soil (see Figure 6.1). Although the combined volume is a tiny fraction of the water on Earth, these pools of water are accessible for movement in and out of the atmosphere and from one place on Earth's surface to another. The average residence time for water in the atmosphere is about 10 days, that for the longest rivers is 20 days or less, and that for soil moisture is about one month.

The Hydrologic Cycle[1]

Solar energy drives the cycling of water from Earth's surface to the atmosphere and back again in what is termed the ***hydrologic cycle*** (Figure 6.2). About one-third of the solar energy that reaches Earth is absorbed by water, stimulating *evaporation* (E)—the conversion of liquid water into water vapor. The water vapor moves up into the atmosphere, eventually forming clouds that can move from one region of the globe to another. Within an average of about ten days, pressure and temperature differences in the atmosphere cause the water vapor to condense into liquid droplets or solid particles, which return to the Earth as rain or other precipitation.

About 483,000 km^3 of water are evaporated from the Earth's surfaces and vegetation each year, some 113,000 km^3 of which falls as rain or snowfall on the continents. Some of the water falling on land runs off the surface of the soil, and some infiltrates into the soil.

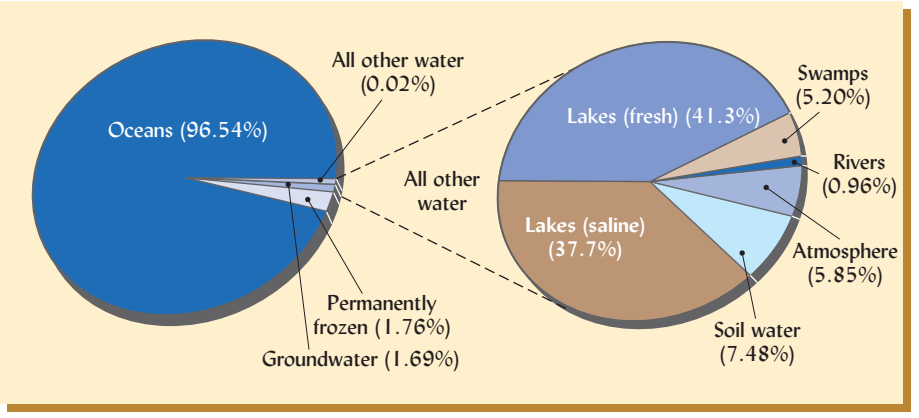

Figure 6.1 *Where is the earth's water? The preponderance of water is found in the oceans, permanent ice and snow (glaciers, ice caps, and soil permafrost), and groundwater* (left) *but most of these waters are inaccessible for rapid exchange with the atmosphere and the land. The sources on the right, though much smaller in quantity, are actively involved in water movement through the hydrologic cycle.* [Calculated and graphed from data in Lal (2015)]

[1]For an in-depth review of the global water cycle see Oki (2011). For assessments of environmental pressures related to global water use see Jeswani and Azapagic (2011) and Pfister et al. (2011).

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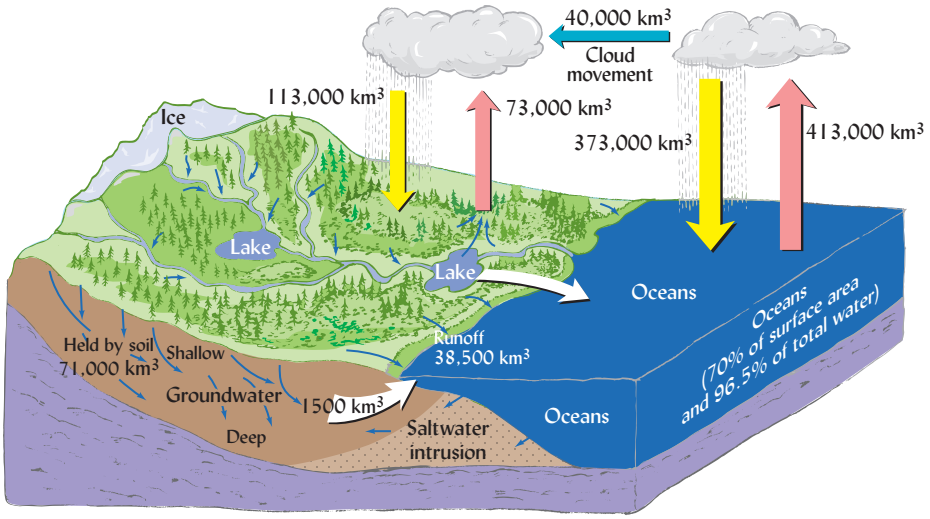

Figure 6.2 *The hydrologic cycle upon which all life depends is very simple in principle. Water evaporates from the Earth's surface, both the oceans and continents, and returns in the form of rain or snowfall. The net movement of clouds brings some 40,000 km³ of water to the continents and an equal amount of water is returned through runoff and groundwater seepage that is channeled through rivers to the ocean. About 85% of the evaporation and 77% of the precipitation occurs in the ocean areas. However, the processes occurring on land areas where the soils are influential have impacts not only on humans but on all other forms of life, including those residing in the sea. Some 65% of the water falling on land becomes sorbed to soil particles at some point in its journey back to the sea.* [Data and concepts from (Brooks, 2015; Lal, 2015)]

About 65% of the water falling on land is bound as soil moisture, most of which is eventually transpired by plants or drains into the groundwater. Both the surface runoff and groundwater seepage enter streams and rivers that, in turn, flow into the oceans. The volume of water returned in this way is about 40,000 km³, which balances the same quantity of water that is transferred annually in clouds from the oceans to the continents.

Water Balance Equation

It is often useful to consider the components of the hydrologic cycle as they apply to a given **watershed,** an area of land drained by a single system of streams and bounded by ridges that separate it from adjacent watersheds (Figure 6.3). All the precipitation falling on a watershed is either stored in the soil, returned to the atmosphere (see Section 6.2), or discharged from the watershed as surface or subsurface runoff. Water is returned to the atmosphere either by

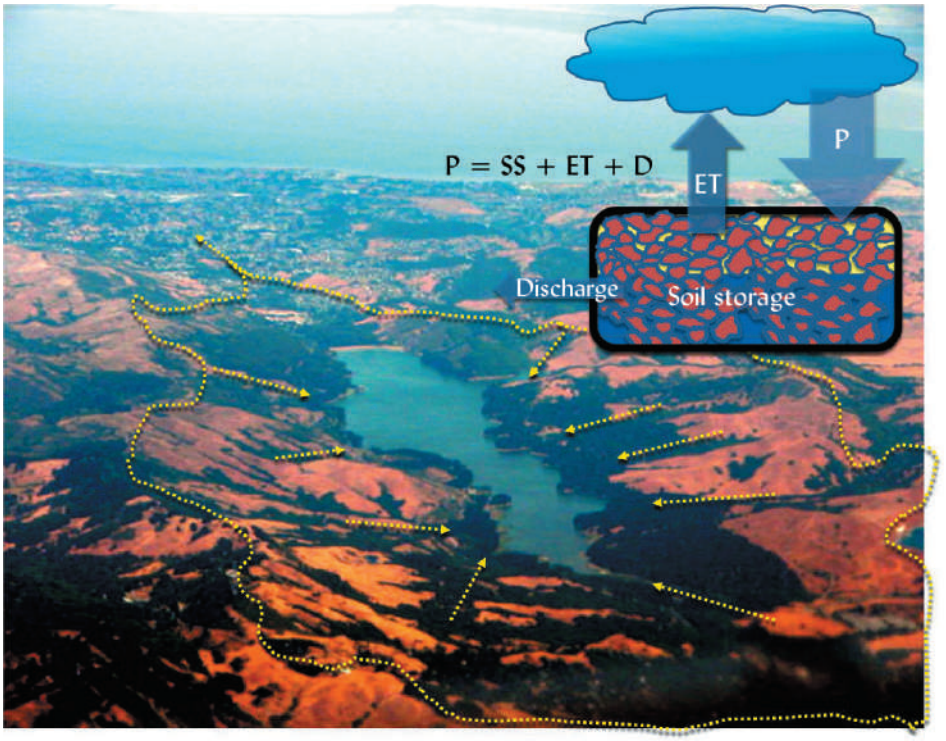

Figure 6.3 *A watershed with a visualization of the water balance equation showing how discharge D (by surface and below ground runoff to streams) is controlled by the proportion of incoming precipitation P that is evapotranspired (ET) from leaf and land surfaces or stored by soils (SS). The yellow arrows represent the general direction of water flow and the dotted yellow line represents the boundary of one particular watershed a landscape near San Francisco in California, USA. A dam has been built across the outlet of the watershed to impound runoff from snowmelt and rainfall for use by the city's residents. After being used for various purposes, the runoff will eventually find its way to the Pacific Ocean in the background.* (Photo and diagram courtesy of Ray R. Weil)

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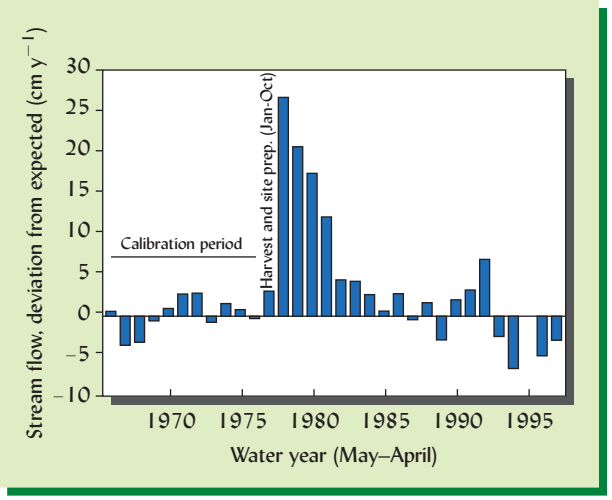

Figure 6.4 *Discharge (stream flow) from a southern Appalachian catchment in the United States before and after commercial clear-cutting of mixed hardwoods. Flow is expressed as cm of water above or below the long-term average flow (as measured prior to the timber harvest). Note the very high values for several years after the trees were felled and the site was prepared for planting. The high flows resulted mainly from reduced transpiration water use in the absence of large trees. Dominated by Typic Hapludults and Typic Dystrochrepts, this 59 ha catchment is part of the Coweeta Hydrologic Laboratory, North Carolina, USA.* [Data from (Swank et al., 2001)]

evaporation from the land surface (vaporization of water from the surfaces of soil, rock, or leaves) or, after plant uptake and use, by vaporization through the stomata in plant leaves (a process termed **transpiration**). Together, these two pathways of evaporative loss to the atmosphere are called **evapotranspiration** (ET).

Water Balance. The disposition of water in a watershed is often expressed by the water-balance equation, which in its simplest form is:

$$P = ET + SS + D \tag{6.1}$$

where P = precipitation, ET = evapotranspiration, SS = soil storage, and D = discharge (Figure 6.3).

Rearranging Eq. (6.1) (D = P − ET − SS) shows that discharge can be increased only if ET and/or SS are decreased, changes that may or may not be desirable. For a forest watershed (sometimes termed a *catchment*) managers may aim to maximize D so as to provide more water to downstream users. Clear-cutting the trees will almost certainly decrease ET and therefore increase discharge (Figure 6.4). In the case of an irrigated field, water applied in irrigation would be included on the left side of Eq. (6.1). Irrigation managers may want to save water applied by minimizing unnecessary losses in D and allowing negative values for SS (withdrawals of soil storage water) during parts of the year (see Section 6.9).

6.2 FATE OF INCOMING WATER

In most climates, a significant portion of incoming precipitation is intercepted by plant foliage (Table 6.1) and returned to the atmosphere by evaporation without ever reaching the soil. Generally, the proportion of precipitation so intercepted increases with higher temperature and decreases with greater humidity and intensity of rainfall. In some forested areas, **interception** may prevent 30–50% of the precipitation from reaching the soil. Interception and subsequent sublimation (vaporization directly from the solid state) of snow is especially important in coniferous forests.

When water from rain or irrigation reaches the soil surface it encounters a very important "fork in the road" along the hydrologic cycle. On one hand, water may follow the path of **infiltration** and enter the soil itself, becoming soil water in the process. Water that reaches the ground is more likely to take this path and infiltrate if the soil surface structure is loose and open. On the other hand, water may take the path of overland flow across the soil surface and become **runoff** that promotes stream flow, but not plant growth and ecosystem productivity.

If the rate of rainfall, irrigation, or snowmelt exceeds the soil's infiltration capacity, some ponding may result (Figure 6.5) and considerable runoff and erosion may take place, thereby reducing the proportion of water that moves into the soil. In extreme cases, more than 50% of the precipitation may be lost as **surface runoff**, which usually carries with it dissolved chemicals, nutrients, and detached soil particles (**sediment**; see Chapter 17).

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Table 6.1
INTERCEPTION OF PRECIPITATION BY SEVERAL TYPES OF PLANT CANOPIES

Canopy type	Location	Percent of precipitation intercepted by canopy
Alfalfa	Missouri, USA	22
Corn	Missouri, USA	7
Soybeans	New Jersey, USA	15
Soybeans	Matto Grosso, Brazil	55
Rainforest	Matto Grosso, Brazil	8
Eucalyptus plantation	Minas Gerais, Brazil	1.4
Ponderosa pine	Idaho, USA	22
Douglas fir	Washington, USA	34
Maple, beech	New York, USA	43
Stone pine, unthinned	Roman Coast, Italy	40
Stone pine, thinned	Roman Coast, Italy	23

USA Crop data from Haynes (1954); USA forest data from Kittridge (1948); Minas Gerais, Brazil data from Steidle Neto et al. (2012); Matto Gross, Brazil data from Bäse et al. (2012); Italy forest data from Mazza et al. (2011).

Figure 6.5 *A small depressional wetland in North Dakota, USA, called a* prairie pothole. *When rain falls faster than the soil infiltration capacity, water will pond on the soil surface and then run off into depressions. In some landscapes with relatively low infiltration capacities, water may stand in depressions for several months. Farmers who cultivate these landscapes with large machinery may view these wetlands (see also Section 7.7) as nuisances in need of drainage. However, small and temporary though they are, wetlands like these scattered across the northern Great Plains in the United States provide nesting sites for about half of the ducks in North America.* (Photo courtesy of Ray R. Weil)

Once water penetrates into the soil, some of it is subject to downward percolation and eventual loss from the root zone by **drainage**. In humid areas and on irrigated land, up to 50% of the water input may be lost as drainage below the root zone. However, during subsequent periods of low rainfall, some of this water may move back up into the plant-root zone by rise of **capillary water**. Such movement is important to plants growing in deep soils, especially in dry climates.

The water retained by the soil is referred to as **soil storage** water, some of which eventually moves upward by capillarity and is lost by evaporation from the soil surface. Much of the remainder is absorbed by plants and then moves through the roots and stems to the leaves, where it is lost by transpiration. The water thus lost to the atmosphere by evapotranspiration may later return to the soil as precipitation or irrigation water, and the cycle starts again.

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Timing of precipitation greatly influences the amount of water moving through each of the pathways just discussed. Heavy rainfall, even if of short duration, can supply water faster than most soils can absorb it. This accounts for the fact that in some arid regions with only 200 mm of annual rainfall, a cloudburst that brings 20–50 mm of water in a few minutes can result in flash flooding and gully erosion. A larger amount of precipitation spread over several days of gentle rain could move slowly into the soil, thereby increasing the stored water available for plant absorption, as well as replenishing the underlying groundwater. As illustrated in Figure 6.6, the timing of snowfall in early winter can affect the partitioning of spring snowmelt water between surface runoff and infiltration. A blanket of snow is good insulation and may keep the soil from freezing.

Effects of Vegetation and Soils on Infiltration

Type of Vegetation. Plants help determine the proportion of water that runs off versus infiltrates the soil. The vegetation and surface residues of perennial grasslands and dense forests protect the porous soil structure from the beating action of raindrops. Therefore, they encourage water infiltration and reduce the likelihood that soil will be carried off by any runoff that does occur. In general, very little runoff occurs from land under undisturbed forests or well-managed turfgrass. However, as Figure 6.7 indicates, differences in plant species, even among grasses, can influence runoff.

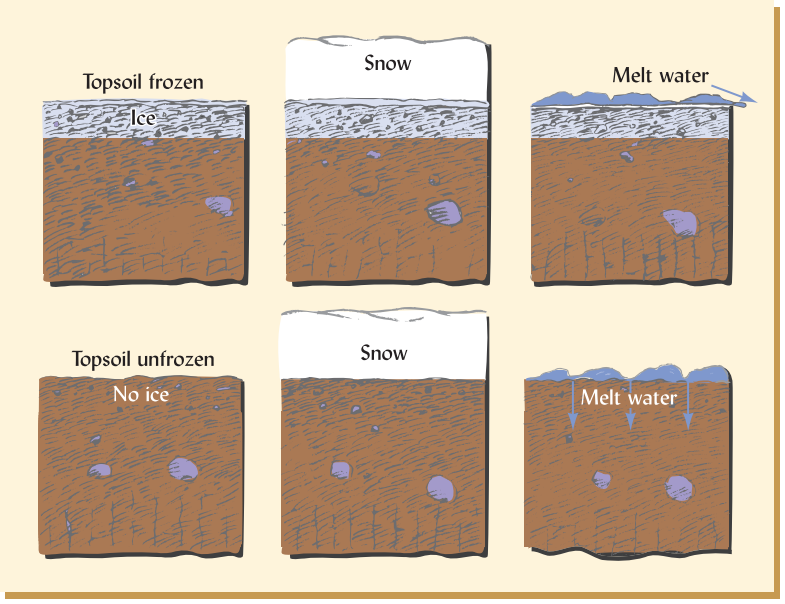

Figure 6.6 *The relative timing of freezing temperatures and snowfall in the fall in some temperate regions drastically influences water runoff and infiltration into soils in the spring. The upper three diagrams illustrate what happens when the surface soil freezes before the first heavy snowfall. The snow insulates the soil so that it is still frozen and impermeable as the snow melts in the spring. The lower sequence of diagrams illustrates the situation when the soil is unfrozen in the fall when it is covered by the first deep snowfall.*

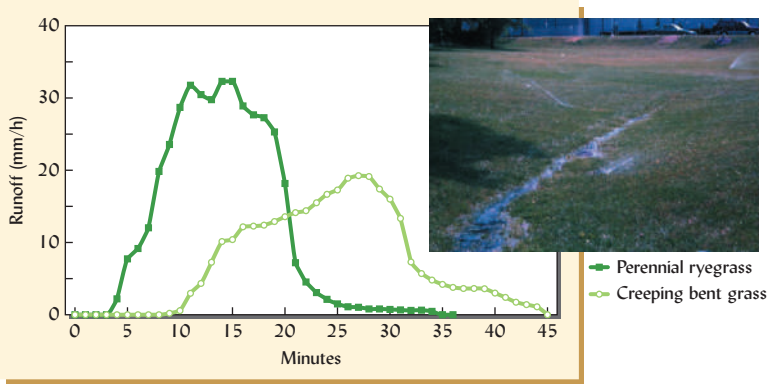

Figure 6.7 *Little water generally runs off turfgrass, except with very intense rainfall, severely compacted soils, or irrigation water applied unevenly or at too high a rate (as shown in the photo). The graph shows runoff from two golf fairway grasses following irrigation at the rate of 150 mm per hour. Note that the runoff peak was much lower on the creeping bent grass, which was characterized by a dense thatch of plant stems and many biopores near the soil surface. A lower rate of irrigation on either type of turf- grass could have eliminated the runoff, which represents a waste of water and a potential for soluble lawn chemicals to be carried to streams and rivers.* [Data from Linde et al. (1995), used with permission of the American Society of Agronomy; photo courtesy of Ray R. Weil]

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Stem Flow. Many plant canopies direct rainfall toward the plant stem, thus altering the spatial distribution of rain reaching the soil. Under a forest canopy, more than half of the rainfall may trickle down the leaves, twigs, and branches to the tree trunk, there to progress downward as **stem flow**. Likewise, certain crop canopies, such as that of corn, funnel a large proportion of the rainfall to the soil in the crop row (Figure 6.8). The concentration of water in limited zones around plant stems increases the opportunity for saturated flow to occur. Stem flow must be considered in studying the hydrology and nutrient cycling in many plant ecosystems.

Soil Management. Encouraging infiltration rather than runoff is usually a major objective of soil and water management. One approach is to allow more time for infiltration to take place by enhancing soil surface storage (Figure 6.9, *left*). A second approach is to maintain dense vegetation during periods of high rainfall. For example, **cover crops**, plants established between the principal crop-growing seasons, can greatly enhance water infiltration by creating open root channels, encouraging earthworm activity, and protecting soil surface structure (Figure 6.9, *right*). However, remember that cover crops also transpire water. If the following

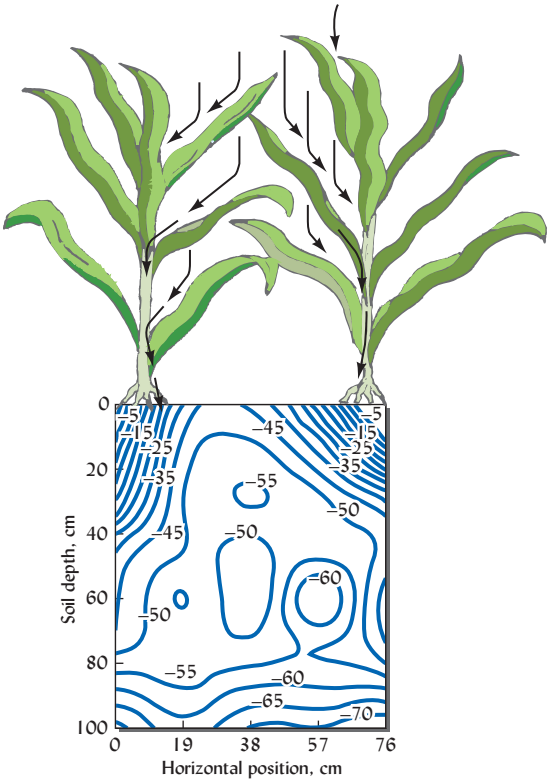

Figure 6.8 *Vertical and horizontal distribution of soil water resulting from stem flow. The contours indicate the soil water potential in kPa between two corn rows in a sandy loam soil. During the previous two days, 26 mm of rain fell on this field. Many plant canopies, including that of the corn crop shown, direct a large proportion of rainfall toward the plant stem. Stem flow results in uneven spatial distribution of water in the soil. In cropland this may have ramifications for the leaching of chemicals such as fertilizers, depending on whether they are applied in or away from the zone of highest wetting near the plant stems. The concentration of water by stem flow may also increase the likelihood of macropore flow in soils after a moderate rainfall.* [Data from Waddell and Weil (1996); used by permission of the Soil Science Society of America]

Figure 6.9 *Managing soils to increase infiltration of rainwater.* (Left) *Small furrow dikes on the left side of this field in Texas, USA, retain rainwater long enough for it to infiltrate rather than run off.* (Right) *This saturated soil under a winter cover crop of hairy vetch is riddled with earthworm burrows that greatly increased the infiltration of water from a recent heavy rain. Scale in centimeters.* [Photo (*left*) courtesy of O. R. Jones, USDA Agricultural Research Service, Bushland, Texas; photo (*right*) courtesy of Ray R. Weil]

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crop will be dependent on soil storage water, care may be needed to kill the cover crop before it can dry out the soil profile.

A third approach is to maintain soil structure by minimizing compaction, whether by people in parks, heavy equipment on farm fields, or cattle on rangeland (see Section 10.1). For example, soil compaction by heavy forestry equipment used to skid logs or clear forestland for agricultural use can seriously impair soil infiltration capacity and watershed hydrology. While the ill effects of compaction can sometimes be partially overcome by deep tillage (see Section 4.7), environmental stewardship requires that caution should be exercised in the use of heavy equipment on any landscape and that disturbance of the natural soil and vegetation be completely avoided on as much of the land as possible.

Urban Watersheds. Built-up landscapes are prime examples where soil compaction affects watershed hydrology. The use of heavy equipment to prepare land for urban development can severely curtail soil infiltration capacity and saturated hydraulic conductivity (Figure 6.10). Soil compaction by construction activity therefore results in drastically increased surface runoff during storms (Figure 6.11). The runoff burden carried by streams in urbanized watersheds is further increased because a large proportion of the land is covered with completely impermeable surfaces (rooftops, paved streets, and parking lots). Erosion of stream banks, toppling of trees, scouring of streambeds, and exposure of once-buried pipelines (Figure 6.12) are typical signs of the environmental degradation that ensues as streams become overwhelmed. Damage to streams in urban watersheds is accentuated because storm sewers and street gutters rush excess water off the land, requiring the stream to carry a huge volume of runoff concentrated in a short period of time. In recognition of the severe environmental problems caused by such excessive and concentrated runoff, urban planners and engineers are now working with soil scientists to reduce disruptions of the hydrologic cycle by urban development. Features such as permeable pavers that allow some infiltration even in parking lots (Figure 6.13, *left*) and rain gardens that catch runoff and release it slowly by infiltration and percolation (Figure 6.13, *right*) are part of what is termed *low impact* urban design.

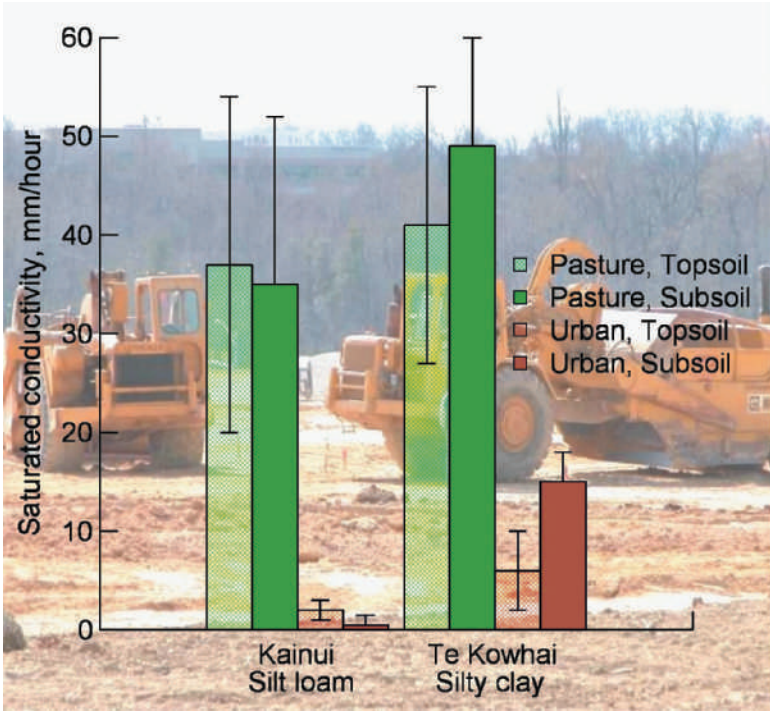

Figure 6.10 *Grading and excavating land in preparation for urban/suburban development can greatly reduce soil permeability and hydraulic conductivity. The impairment results from compaction, damage to soil structure, and profile truncation (removal of A horizon). Both topsoil and subsoil horizons in these two New Zealand soils suffered three- to tenfold reductions in saturated hydraulic conductivity when the land was converted from a pasture to a housing development. The vertical lines indicate the variation among repeated measurements in the same soil, this variation being especially large in the pasture soils because of the random presence of earthworm channels.* [Data from Zanders (2001), used with permission from Landcare Research NZ Ltd.; photo courtesy of Ray R. Weil]

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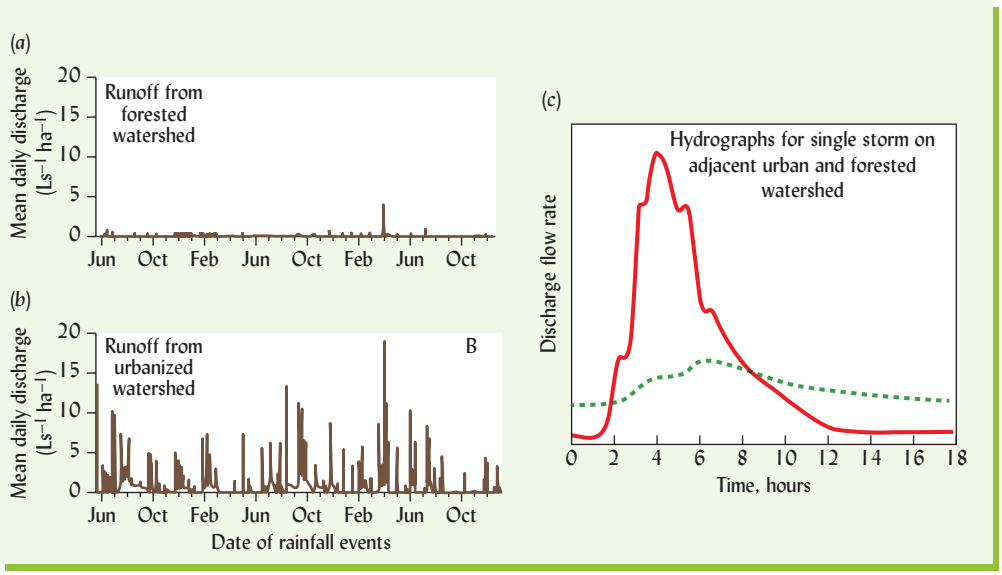

Figure 6.11 *Hydrographs showing much greater, flashier and more frequent runoff events from an urbanized watershed* (b) *compared to an adjacent forested watershed* (a) *subject to the same rainfall events near Atlanta in Georgia, USA.* (c) *A representative single storm hydrograph showing the difference in intensity of discharge and level of base flow from adjacent urbanized and forested watersheds.* [Graphs (*a*) and (*b*) adapted from Nagy et al. (2011), graph (*c*) courtesy of Ray R. Weil]

Figure 6.12 *Signs of excessive runoff from urbanized land.* (Left) *Exposure of a once-buried storm sewer manhole along a highly degraded stream that collects runoff from part of Baltimore in Maryland, USA. The drastically increased storm runoff volume from the largely impermeable urban watershed has caused the stream to erode its banks and deeply cut into the hillside. The round manhole cover indicates the former land surface.* (Right) *The toppled tree and scoured soil are signs that this placid appearing small stream is overwhelmed by raging torrents of water during heavy rainfalls because the urbanized watershed conducts the water more directly and rapidly to the stream than did the natural watershed that formed the stream.* (Photos courtesy of Ray R. Weil)

Soil Properties. Inherent soil properties also affect the fate of precipitation. If the soil is loose and open (e.g., sands and well-granulated soils), a high proportion of the incoming water will infiltrate the soil, and relatively little will run off. In contrast, heavy clay soils with unstable soil structures resist infiltration and encourage runoff. These differences, attributable to soil properties as well as vegetation, are illustrated in Figure 6.14. Other factors that influence the balance between infiltration and runoff include the slope of the land (steep slopes favoring runoff over infiltration; see Box 2.1) and impermeable layers within the soil profile. Such impermeable layers as fragipans (see Figure 3.30) and clay pans can restrict infiltration and increase surface runoff once the upper horizons become saturated, even if the surface soil has intact structure and high porosity (Figure 6.15).

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Figure 6.13 *Two methods of increasing infiltration and slowing runoff in urbanized watersheds.* (Left) *Permeable pavers allow grass to grow and water to infiltrate a parking lot while cars can still park without compacting soil or forming mud.* (Right) *Water entering one of several small rain gardens that capture runoff from a suburban parking lot. The water is directed to a small depression. The small pond that forms is ephemeral, holding the runoff water only temporarily. Permeable soil placed under the depression along with buried drain pipes are designed to allow the water to infiltrate and seep away over a period of a few hours. The depression is planted with a variety of native plants that provide both beauty and wildlife habitat.* (Photos courtesy of Ray R. Weil)

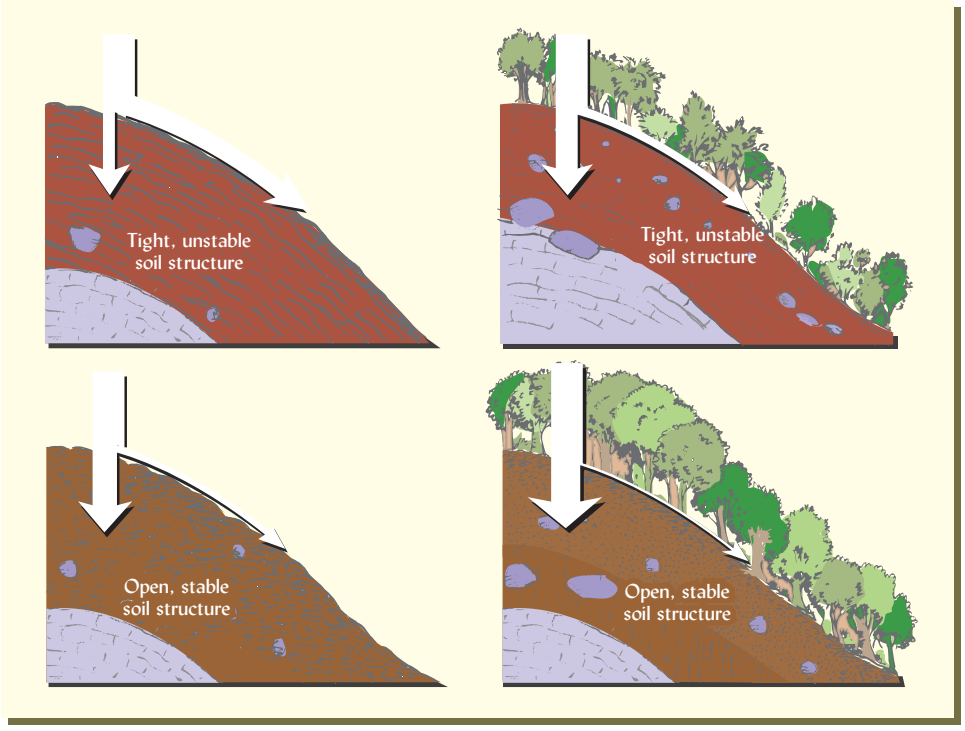

Figure 6.14 *Influence of soil structure and vegetation on the partitioning of rainfall into infiltration and runoff. The upper two diagrams show soils with tight, unstable, or compacted structure that resists infiltration and percolation. The bare soil is especially prone to surface sealing and resulting high losses by runoff. Even with forest cover, the low-permeability soils cannot accept all the rain in an intense storm. The two lower diagrams show much greater infiltration into soils that have open, stable structures with significant macropore space. The more open soil structure combined with the protective effects of the forest floor and tree canopy nearly eliminate surface runoff.* (Diagram courtesy of N. C. Brady)

The burrowing and nesting activities of certain soil animals that produce a network of macropores connected to the soil surface can also enhance infiltration, reduce runoff losses, and thereby improve water availability for plants. Such enhancement of soil hydrologic function by earthworms is a well-known phenomenon in humid temperate regions. The research described in Figure 6.16 suggests that ants and termites can similarly increase soil productivity

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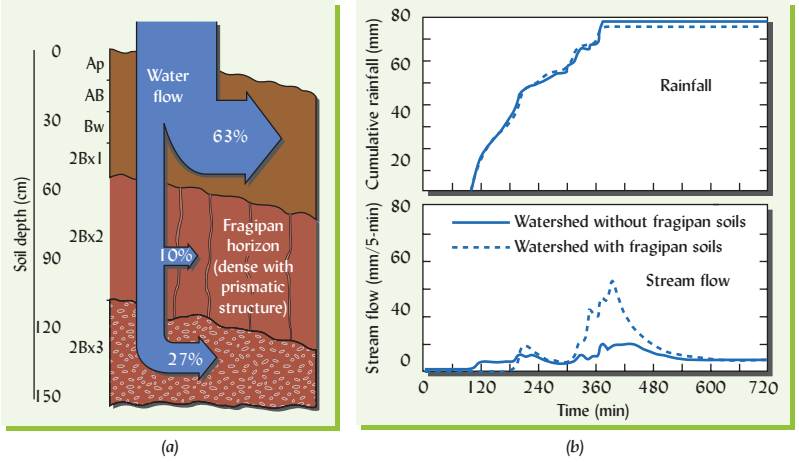

Figure 6.15 *Soil profile characteristics largely determine the vertical and lateral movement of water, including runoff from watersheds during rainstorms. In this example, a fragipan* (left, *also see Figure 3.30) provides a barrier to both root growth and downward percolation of water. The zone above the fragipan may become saturated during wet weather, giving rise to a perched water table. As more rain falls, little can enter the already saturated surface horizons. Most of the water flows laterally, either through the soil above the fragipan or as surface runoff. The graphs* (right) *show the cumulative rainfall* (upper) *and volume of stream flow* (lower) *during and after a storm in which nearly 80 mm of rain fell in a 300-minute period. Of the two small (13–20 ha) watersheds represented, one has a large area of fragipan-containing soils (Fragiochrepts) formed in colluvium near the stream channel; the other watershed has no such fragipans. Although the rainfall was almost identical for the two nearby watersheds, stream flow (both the maximum and the overall volume) was much greater for the watershed with fragipans than the one without these impermeable layers.* (Soil profile based on data in Day et al. (1998); graphs from Gburek et al. (2006), with permission of Elsevier Science, Oxford, United Kingdom)

in dry tropical regions. More information on the activities of soil animals can be found in Sections 11.4 and 11.5.

All the soil and plant factors just discussed can result in some parts of a landscape contributing more runoff than others. Such spatial heterogeneity of infiltration and runoff is particularly important to ecosystem function in dry regions (see Box 10.1).

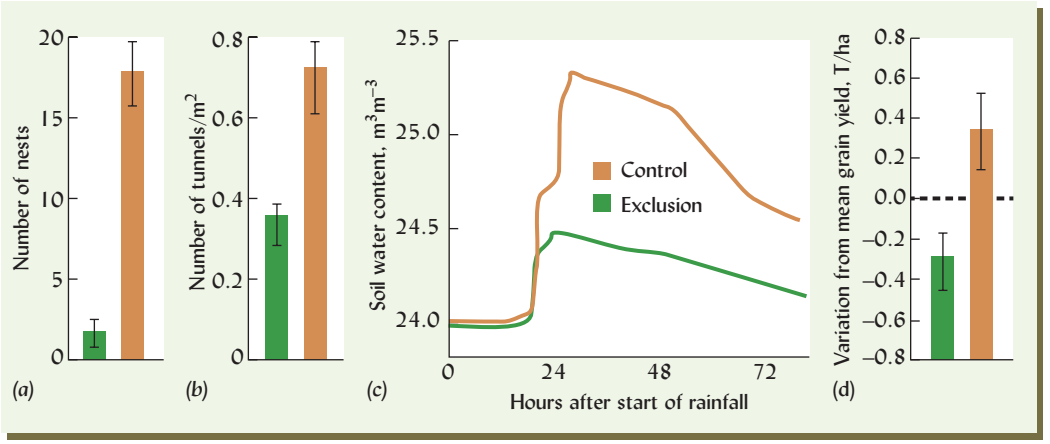

Figure 6.16 *Ants and termites increase soil water supply and plant productivity in a semi-arid tropical region. The research summarized here was conducted in a hot and dry (284 mm rain /year) part of Western Australia with infertile, sandy soils (Dystric Xeropsamments) and Eucalyptus and Acacia dominated natural vegetation. The experimental area was cleared and managed in a wheat-fallow-wheat rotation for 20 years prior to the experiment. The experiment compared soil management with or without an insecticidal drench consisting of pyrethroids that kill insects but have little effect on soil microorganisms. The insecticide succeeded in excluding nearly all ants and termites (panel* (a)*). Although some pre-existing insect tunnels remained in the exclusion plot soils, the density of tunnels was much lower than where no insecticide was used. The tunnels and nests of ants and termites provided surface macropores that greatly enhanced water infiltration into the soil during rain events* (c)*. Greater infiltration rates and resulting better water availability in the soil profile were mainly responsible for the higher wheat yields observed. Wheat yields* (d) *were below average where insects were excluded and above average where they were present. Overall, the ecosystem services of the ants and termites increased wheat production by some 36%. Green = insects excluded, brown = control.* [Redrawn from Evans, et al. (2011)]

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6.3 THE SOIL–PLANT–ATMOSPHERE CONTINUUM (SPAC)[2]

The flow of water through the SPAC is a major component of the overall hydrologic cycle. Figure 6.17 ties together many of the processes we have just discussed: *interception, surface runoff, percolation, drainage, evaporation, plant water uptake, ascent of water to plant leaves,* and *transpiration* of water from the leaves back into the atmosphere.

Water Potentials. In studying the SPAC, scientists have discovered that the same basic principles govern the retention and movement of water whether it is in soil, in plants, or in the atmosphere. In Chapter 5, we learned that water in soil moves to where its potential energy level will be lower. This principle applies to water movement between the soil and the plant root and between the plant and the atmosphere (see Figure 6.17). If a plant is to absorb water from the soil, the water potential must be lower (greater negative value) in the plant root than in the soil adjacent to the root. Likewise, movement up the root and stem to the leaf cells is in response to differences in water potential, as is the movement from leaf

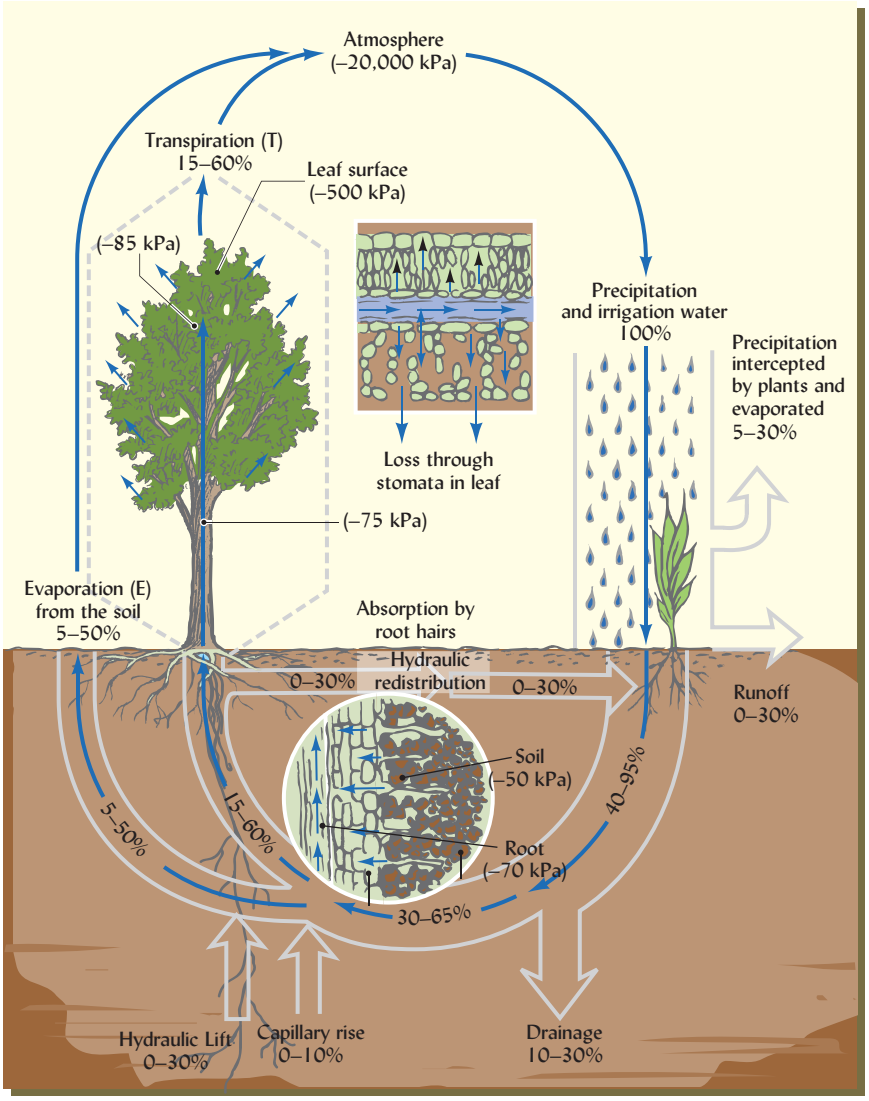

Figure 6.17 *Soil–plant–atmosphere continuum (SPAC) showing water movement from soil to plants to the atmosphere and back to the soil. As described for soil water movement in Chapter 5, water in the entire SPAC moves from a higher to a lower moisture potential. Note that the moisture potential in the soil is –50 kPa, dropping to –70 kPa in the root, declining still further as it moves upward in the stem and into the leaf, and is very low (–500 kPa) at the leaf–atmosphere interface, from whence it moves into the atmosphere, where the moisture potential is –20,000 kPa. Note the suggested ranges for partitioning of the precipitation and irrigation water as it moves through the continuum. Most of the water absorbed by plant roots is eventually transpired as water vapor, but a significant proportion may be exuded by roots into soil zones that are drier than the zones from which the water was initially taken up—a process termed hydraulic redistribution.* (Diagram courtesy of Ray R. Weil and N. Brady)

[2]The physics of water movement in plants has been quite controversial at times. For strong evidence that confirms that water moves up tall trees by the same capillary forces that control its movement in soil, see Tyree (2003).

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surfaces to the atmosphere. To illustrate the movement of water to sites of lower and lower water potential, Figure 6.17 shows that water potentials might drop from −50 kPa in the soil, to −70 kPa in the root, to −500 kPa at the leaf surfaces, and, finally, to −20,000 kPa in the atmosphere.

Two Points of Resistance. Water encounters major resistance to its movement as it crosses cell membranes at the root–soil water interface and again at the leaf–atmosphere interface. This means that two primary factors determine whether plants are well supplied with water: (1) the rate at which water is supplied by the soil to the absorbing roots, and (2) the rate at which water is transpired from the plant leaves. Since factors affecting the soil's ability to supply water were discussed in Section 5.9, we will now address the loss of water by evaporation from soil–plant systems.

Evapotranspiration

While it is relatively easy to measure the total change in soil water content due to vapor losses, it is quite difficult to determine just how much of that loss occurred directly from the soil (by E) and how much occurred from the leaf surfaces after plant uptake (by T). Therefore, information is most commonly available on ET, the combination of these two processes. The evaporation component of ET may be viewed as a "waste" of water from the standpoint of plant productivity. On the other hand, at least some of the transpiration component is essential for plant growth, providing the water that plants need for cooling, nutrient transport, photosynthesis, and turgor maintenance.

The **potential evapotranspiration** (PET) rate tells us how fast water vapor *would* be lost from a densely vegetated plant–soil system *if* soil water content were continuously maintained at an optimal level. The PET is largely determined by the *vapor pressure gradient* between a wet soil, leaf, or body of water and the atmosphere. This gradient is in turn influenced by solar radiation and such related climatic variables as temperature, relative humidity, cloud cover, and wind speed.

A number of mathematical models have been devised to estimate PET from climatological data, but in practice, PET can be most easily estimated by applying a correction factor to the amount of water evaporated from an open pan of water of standard design (a class A evaporation pan; see Figure 6.18). Because of the resistances to water flow just mentioned, water loss by transpiration from well-watered, dense vegetation is typically only about 65% as rapid as loss by evaporation from an open pan; hence, the correction factor for dense vegetation such as a lawn is typically 0.65 (it is lower for less dense vegetation):

$$\text{PET} = 0.65 \times \text{pan evaporation} \tag{6.2}$$

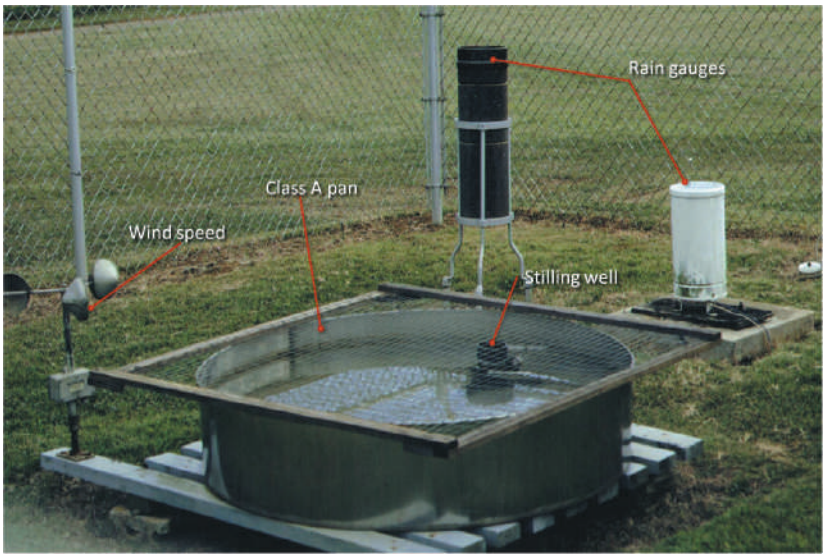

Figure 6.18 *A class A evaporation pan used to help estimate potential evapotranspiration (PET). Once a day, the water level is determined in the stilling well (small cylinder) and a measured amount of water is added to bring the level back up to the original mark. Evaporation from the pan integrates the effects of relative humidity, temperature, wind speed, and other climatic variables related to the vapor pressure gradient. Also shown is an anemometer to measure wind speed and gauges to measure precipitation.* (Photo courtesy of Ray R. Weil)

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Values of PET range from more than 1500 mm per year in hot, arid areas to less than 40 mm in very cold regions. During the winter in temperate regions, PET may be less than 1 mm per day. By contrast, hot, dry wind will continually sweep away water vapor from a wet surface, creating a particularly steep vapor pressure gradient and PET levels as high as 10–12 mm per day.

Effect of Soil Moisture. Evaporation from the soil surface at a given temperature is determined largely by soil surface wetness and by the ability of the soil to replenish this surface water as it evaporates. In most cases, the upper 15–25 cm of soil provides most of the water for surface evaporation. Unless a shallow water table exists, the upward capillary movement of water is very limited and the surface soil soon dries out, greatly reducing further evaporation loss.

However, because plant roots penetrate deep into the profile, a significant portion of the water lost by evapotranspiration can come from the subsoil layers. As discussed in Chapter 5 (see Figure 5.45) native vegetation rooting depths suggest that water stored deep in the profile is especially important in regions having alternating moist and dry seasons (such as Ustic or Xeric moisture regimes). Water stored in the subsoil during rainy periods is available for evapotranspiration during dry periods. Vegetation may go dormant—or die—because of the inability of a shallow soil to hold sufficient water during prolonged dry periods (see Figure 5.43 illustrating the death of a rooftop lawn).

Plant Water Stress. For dense vegetation growing in soil well supplied with water, ET will nearly equal PET. When soil water content is less than optimal, the plant will not be able to withdraw water from the soil fast enough to satisfy PET. If water evaporates from the leaves faster than it enters the roots, the leaves will lose turgor pressure and wilt. Under these conditions, actual evapotranspiration is less than potential evapotranspiration and the plant experiences *water stress.* The difference between PET and actual ET is termed the *water deficit.* A large deficit is indicative of high water stress and aridity.

Under water-stress conditions, plants first close the *stomata* (openings) on their leaf surfaces to reduce the vapor loss of water and prevent wilting or possible cell collapse. However, the closure of the stomata has two detrimental side effects: (1) plant growth is arrested because insufficient CO_2 for photosynthesis can pass through the closed stomata, and (2) the reduction in evaporative cooling results in detrimental *heating* of leaves as they continue to absorb solar radiation. The latter effect allows infrared-detecting instruments to estimate water stress in plants by sensing the increase in leaf temperature over air temperature. Stomatal closure in response to low leaf water potentials may also be "too little, too late" for plant survival.

Plant Characteristics. In vegetated areas, as the leaf area per unit land area (a ratio termed the **leaf area index** (LAI)) increases, more radiation will be absorbed by the foliage to stimulate transpiration and less will reach the soil to promote evaporation. For a monoculture of annual plants, the LAI value typically varies from 0 at planting to a peak of perhaps 3–5 at flowering, then declines as the plant senesces, and finally drops back to 0 when the plant is removed at harvest (assuming no weeds are allowed to grow). In contrast, perennial vegetation, such as in pastures and forests, has very high leaf area indices both early and late in the growing season. Where leaf litter has accumulated on the forest floor, very little direct sunlight strikes the soil, and evaporation is very low throughout the year (Figure 6.19). Other plant characteristics, including rooting depth, length of life cycle, and leaf morphology, can influence the amount of water lost by evapotranspiration over a growing season. Figure 6.20 illustrates the comparative competitiveness of mature trees and annual crops for soil water supplies.

Water Use Efficiency. **Water use efficiency** may be expressed in terms of plant dry matter produced per unit of water transpired (*T efficiency*) or per unit of water lost by evapotranspiration (*ET efficiency*). Agriculturalists commonly express water use efficiency as kg of grain produced per m^3 of water used in evapotranspiration (see Figure 6.21). For irrigation systems

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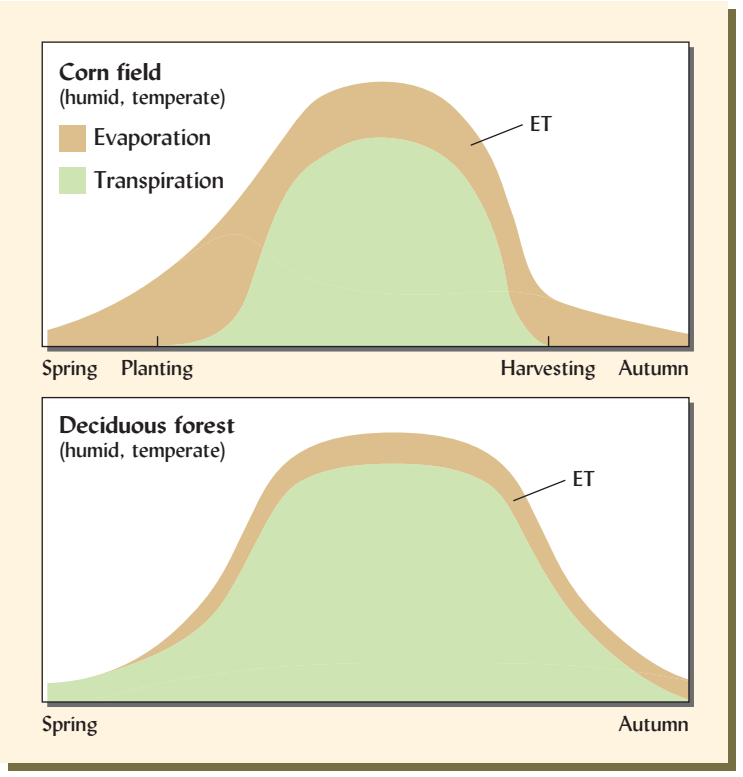

Figure 6.19 *Relative rates of evaporation from the soil surface E, of transpiration from the plant leaves T, and the combined vapor loss ET for a tilled field of corn* (upper) *and a deciduous forest* (lower), *both in a temperate humid region. Early in the season when the corn plants are small, most of the vapor loss is from the bare soil surface E. As the plants grow, T soon dominates, the soil surface becomes shaded and E may decrease somewhat. As the plants reach maturity, the corn leaves senesce causing T to decline. As temperatures are cooler at the end of the season, the combined ET also declines. For a nearby deciduous forested area the same general trend is illustrated, except there is relatively less evaporation from the soil surface and a higher proportion of the vapor loss is by transpiration. The soil is shaded by the leaf canopy most of the growing season, as well as by the litter layer so E is very low at all times. It should be noted that these figures relate to a representative situation and that the actual field losses would be influenced by rainfall distribution, temperature fluctuations, and soil properties.* (Diagram courtesy of Ray R. Weil)

Figure 6.20 *Water-stressed soybeans show the extent of tree root competition for water in the surface soil.* (Photo courtesy of Ray R. Weil)

analysis, water use efficiency may consider additional aspects such as losses of water in storage reservoirs or leakage from canals (see Section 6.10).

Whatever the units of expression, data from studies around the world show that huge amounts of water are needed to produce the human food supply and that water use efficiency is largely driven by climatic factors. In arid regions, crops may use 1000 to more than 5000 kg of water to produce a single kg of grain. Ironically, in more humid regions where water and rain are plentiful, much less water is needed for each kg of grain produced because the evaporative demand is far lower.

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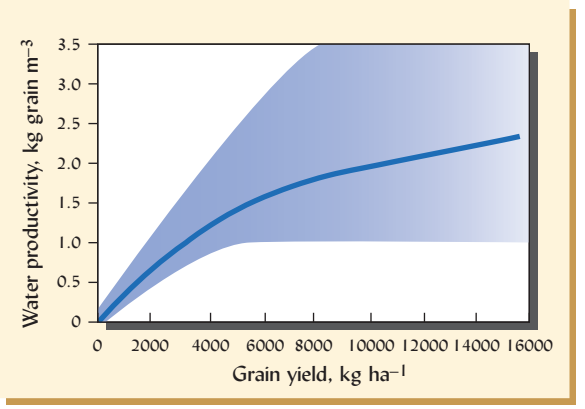

Figure 6.21 *Evapotranspiration water-use efficiency, the dry matter produced for every unit of water used on the crop, generally increases as crop yield increases. This is true mainly because such yield-improving measures as fertilizer use, better cultivars, denser stands, and better pest control generally increase crop yield by a greater proportion than they do the use of water. This relationship generally applies where water is available to meet the demands of higher-yielding crops. Even so, the curve levels off above 1.5 kg grain per 1000 kg water (1 m^3 = 1000 kg water). The shaded area represents the range of data recorded for irrigated and nonirrigated (dryland) wheat, rice, and corn crops.* [Based on data in Howell (2001) and Molden et al. (2010)]

ET Efficiency. Since evapotranspiration includes both transpiration from plants and evaporation from the soil surface, evapotranspiration efficiency is more subject to management than transpiration efficiency. Highest ET efficiency is attained where plant density and other growth factors minimize the proportion of ET attributable to evaporation from the soil. Figure 6.21 illustrates the relationship generally found between crop yields and water use efficiency. Higher yielding plants generally send their roots deeper into the soil profile and produce a denser canopy (higher LAI) that allows less solar radiation to pass through and cause evaporation from the soil surface. We can conclude that as long as the supply of water is not too limited, maintaining optimum conditions for plant growth (by closer plant spacing, fertilization, or selection of more vigorous varieties) increases the efficiency of water use by plants. If irrigation water is not available and the period of rainfall is very short, one should apply this principle with caution. The increase in evapotranspiration by more vigorously growing plants may deplete stored soil water, resulting in serious water stress or even plant death before any harvestable yield has been produced!

Hydraulic Redistribution.[3] Plant roots not only remove water from the soil, but they also can release water back into the soil. During the day when leaf stomata are open and atmospheric conditions favor evaporation, transpiration water losses through the leaves generate low soil water potentials (large negative values) inside the plant stem and root cells. As the water potential in the root becomes lower than that in the adjacent soil, water moves into the roots and is taken up by the plant. In turn, as water is removed from the soil, the potential of the remaining soil water decreases (exhibits larger negative values). During the night when atmospheric humidity is high and the leaf stomata are closed, the process is reversed. Without the "pull" of transpiration, the water potential in the roots is increased, increasing turgor pressure inside the plant cells. As the water potential inside the roots become higher than that in the surrounding soil, water begins to move from the root out into the soil where its potential will be lower (Figure 6.22).

Recent research by soil and plant scientists has clearly shown that the mechanisms just described, allow plant roots to serve as conduits for moving significant amounts of water from moist soil zones to dry soil zones, a process termed **hydraulic redistribution.** The importance of vertical hydraulic redistribution, or **hydraulic lift**, has been especially well documented for woody plants. In contrast to the competitive situation shown in Figure 6.20, deep-rooted trees can transfer water from moist soil layers many meters deep to surface soil layers. During long dry periods, this added water ensures the survival and growth of shallower rooted understory grass and herbaceous vegetation as well as the functioning of soil microbial systems that improve plant growth, including that of the trees. For example, sage brush, a deep-rooted woody plant found in the deserts of south western North America, conducts enough hydraulic redistribution to enhance the microbial mineralization of nitrogen from organic matter in surface soil and supply a third to one half of the water used by relatively shallow-rooted crested wheatgrass growing nearby.

[3]For a review of ecosystem implications of hydraulic redistribution of soil water by plants, see Prieto et al. (2012).

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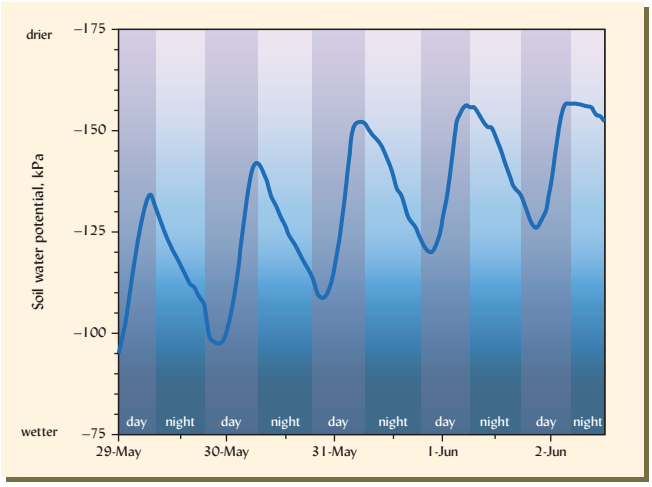

Figure 6.22 (Left) *The daily fluctuations of soil water tension measured at 50-cm depth in the root zone of a corn crop reflect the cycle of water uptake from the soil during the day and exudation into the soil during the night. Note that the overall trend during the 5-day rainless period shown is one of soil drying (increasing tension = decreasing potential).* (Right) *Water is being exuded by a cut plant stem in another soil. The plant is growing in soil that has high water content at depth, but has dried out in the surface horizons. The plant stem was cut on a cool, cloudy day with low evaporative demand such that a high (positive) water potential had built up in the cells. The plants shallow roots can be expected to also exude water into the surface soil, though more slowly than is the case for the cut stem.* [Graphed from data of Chen and Weil (2011). Photo courtesy of Ray R. Weil]

Research in Japan and elsewhere suggest that the process of hydraulic lift may be manipulated to create "self-irrigating" agroecosystems in which rows of deep-rooted "water donor" plants alternate with water-receiving areas planted to shallow rooted but high-value vegetable crops (Figure 6.23).

In summary, water losses from the soil surface and from transpiration are determined by: (1) climatic conditions, (2) plant cover in relation to soil surface (LAI), (3) efficiency of water use by different plants and management regimes, and (4) length and season of the plant-growing period. In addition, the ability of plant roots to redistribute water from moist soil to drier soil can alter natural vegetation communities and provide enough water to shallow-rooted species to ensure their survival and possibly improve crop production.

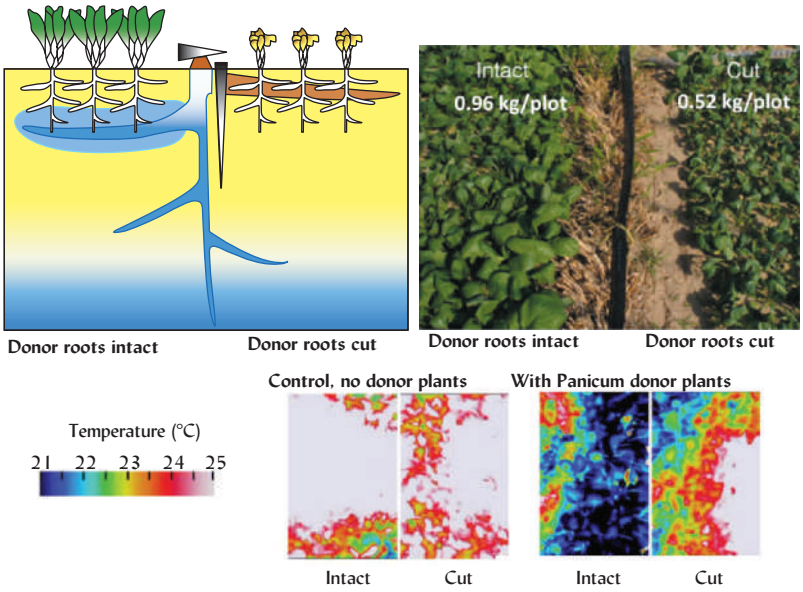

Figure 6.23 *An experimental agroecosystems using hydraulic lift to "self-irrigate."* (Upper left) *Vertical cross-section diagram of a field plot with shallow-rooted kale* (Brassica rapa) *plants in a plot with deep-rooted grass* (Panicum maximum) *donor plants. The shoots of the donor plant were cut to induce root exudation of water by the donor plant roots.* (Upper right) *The donor plant roots were left intact on the left side but they were cut on the right side so no water could be distributed there.* (Lower) *Thermal images of the* Brassica rapa *plants grown under field conditions without associated donor plants (Control) and with* Panicum *donor plants. The redder colors indicated higher leaf temperatures in water-stressed plants. Note the blue, nonwater stressed plants adjacent to the donor plants whose roots were left intact so they could redistribute water from deep moist layers in this sandy soil.* [Modified from Sekiya et al. (2011)]

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6.4 CONTROL OF ET

Because transpiration is closely related to the total leaf area exposed to solar radiation and evaporation is related to the amount of soil surface so exposed, measures taken to reduce these exposures can bring ET into closer balance with the available water supply and may, to some degree, lessen water stress on desirable vegetation.

Control of Transpiration

In various agricultural situations it may be necessary to limit transpiration by desirable plants (e.g., crops) and/or unwanted (weedy) vegetation. Where rapid crop growth might prematurely deplete the water available, it may be wise to limit plant growth factors such as nutrient supply to only moderate levels, thus keeping LAI in check. The LAI of desired plants can also be limited by spacing plants farther apart, as nature does in arid environments. It should be noted, however, that plants growing farther apart tend to individually produce a greater leaf area, compensating somewhat for the lower density. Also, wider spacing allows greater evaporation losses from the soil.

Unwanted Vegetation. It is largely through their heavy use of soil water that weeds interfere with the establishment and growth of desirable forest, range, and crop plants. Weeds in cropland have traditionally been controlled by cultivation (light soil tillage) designed to uproot young weeds and leave them to dry out and die. Disadvantages of cultivation include likely damage to roots of nearby desired plants and the exposure of bare soils, which in turn increases evaporative water loss and eventually encourages runoff and erosion.

Herbicides. In recent decades weeds have been widely controlled by spraying weed-killing chemicals called herbicides (see Section 18.2). Weed control with herbicides has several advantages over cultivation, among which are that it requires less labor and energy, and it allows the soil to be left undisturbed, with plant residues covering the soil surface (see below). Chemical weed control also has serious disadvantages in some situations, including high material costs, eventual evolution of weed resistance to specific compounds, damage to desired plants (including subsequently planted crops or cover crops). Herbicides also present risks of environmental toxicity. Herbicides may be toxic to soil organisms, fish, or land animals, including carcinogenicity to humans. In many case herbicides have accumulated to undesirable levels in downstream waterways and underground drinking water sources (see Section 18.3).

Alternative Weed Controls. Consequently, alternative weed control methods are being sought. For example, some weeds can be held in check by biological controls, that is, encouraging specific insects or diseases that attack only the weeds. Undesirable vegetation in rangeland and some forests can be suppressed by prescribed fires if the timing and temperature levels are carefully controlled to minimize damage to desirable vegetation. Well-timed mowing or grazing can also reduce weed problems in pastures.

Cover crops can be used to reduce weed pressure in subsequent crops through competitive and chemical effects on weed seed germination. In most cases the cover crops are terminated and weeds controlled with the help of herbicides. Certain cover crops can be rolled down and killed mechanically to produce a thick weed-smothering mat of residues. These cover crops can be combined with weed control using new implements designed to cultivate through the high levels of plant residue by undercutting the roots of emerging weeds without disturbing the soil surface. Such techniques hold promise for controlling weeds in humid regions without herbicides while still maintaining the desirable surface residue cover (Figure 6.24).

Fallow in Dryland Cropping. Farming systems that alternate bare **fallow** (unvegetated period) one year with traditional cropping the next have been used to conserve soil moisture in some low-rainfall environments. Transpiration water losses during the fallow year are minimized by controlling weeds with light tillage and/or with herbicides. Some of the water saved during the fallow year remains in the profile the following year when a crop is planted, resulting in higher yields of that second-year crop than if the soil had been cropped every year. This

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Figure 6.24 *Cover crops and new mechanical weed control implements can help minimizing vapor losses of water from row-crop soil while planting the crop without tillage and without herbicides.* (a) *Mechanical termination of a rye cover crop using a roller-crimper mounted on the front of the tractor to avoid leaving rye unkilled in the tire tracks. A no-till planter mounted on the rear of the tractor is simultaneously sowing soybean seed into the freshly rolled and crimped cover crop residue mulch.* (b) *The resulting thick mulch of killed rye residue all but eliminates evaporation losses of water from the soil between soybean rows and suppresses most weed growth early in the season. The weeds that eventually did emerge through the mulch can be killed using a high residue cultivator that slices and lifts the soil under the mulch while leaving the surface mulch largely undisturbed.* (c) *The high residue cultivator works by cutting a slit through the mulch with sharp rolling coulters followed by a V-shaped sweep that slices and lifts the soil under the mulch to destroy the roots of young weeds growing between the soybean rows. This technology is of particular relevance to organic farming in which use of synthetic weed killing chemicals is not allowed.* (Photo © Rodale Institute)

cropping practice is responsible for the checkerboard of dark fallow soils and golden ripening wheat that can be seen when flying over such semiarid "breadbaskets" as the Great Plains region of the United States and Canada.

The main disadvantage of this system is the soil degradation that occurs, largely because of a negative soil organic matter balance (see Section 12.7) and wind erosion (see Section 17.11) during the fallow years. The growing use of conservation tillage practices (see below and Section 17.6) in semiarid areas has led to sufficient savings in soil moisture to minimize the need for fallow cropping (Figure 6.25). Conservation tillage practices (including "no-till") leave most of the crop residues on the soil surface where they reduce evaporation and protect the soil. From research at many sites we can now conclude that long-term productivity, profitability, and soil quality are likely to be optimized with cropping systems that use conservation tillage and keep the soil continuously vegetated with a diversity of crops. Dozens of long-term studies in the semiarid North American Great Plains region have compared cropping systems with or without summer fallow and in virtually every case the system without fallow was most productive. Results like these are encouraging farmers to abandon summer fallow in favor of reduced tillage rotations that yield more grain and better maintain soil quality.

Control of Surface Evaporation

More than half the precipitation in semiarid and subhumid areas is usually returned to the atmosphere by E directly from the soil surface. In natural rangeland systems, E is a large part of ET because plant communities tend to self-regulate toward configurations that minimize the deficit between PET and ET—generally low plant densities with large unvegetated areas between scattered patches of shrubs or bunchgrass. In addition, plant residues on the soil surface are sparse. Evaporation losses are also high in arid-region irrigated soil, especially if inefficient practices are used (see Section 6.9). Even in humid-region rain-fed areas, E is significant during hot, rainless periods. Such moisture losses rob the plant community of much of its growth potential and reduce the water available for discharge to streams. Careful study of Figure 6.26 (*left*) will clarify these relationships and the principles just discussed. Note that the gap between PET and ET represents the *soil water deficit.* The global map in Figure 6.26 (*right*) suggests where and to what degree the soil water supply is limiting for plant productivity.

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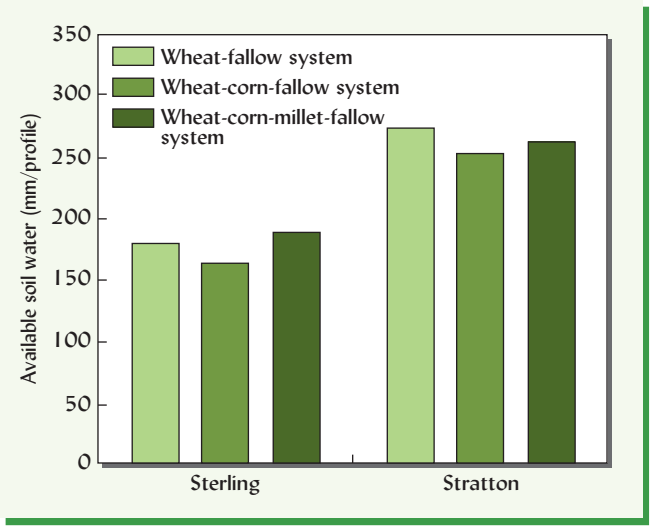
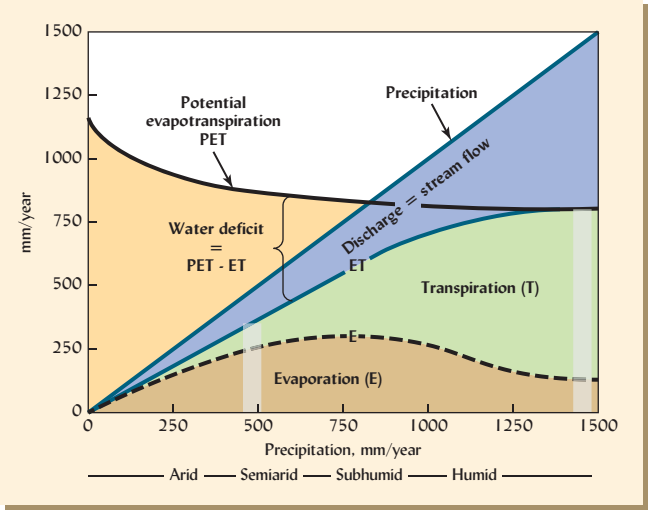


Figure 6.25 *Available water (mm/profile) in the soil profile at wheat planting time in systems with fallow every second, third, or fourth year at two semiarid locations in eastern Colorado, USA, where conservation tillage practices had been adopted. Note that the available soil water level was about the same whether the soil was fallowed every other year or every third or fourth year. Apparently soil evaporation losses were so high during the fallow years that little additional water was conserved by leaving the land fallow.* [Redrawn from Farahani et al. (1998)]



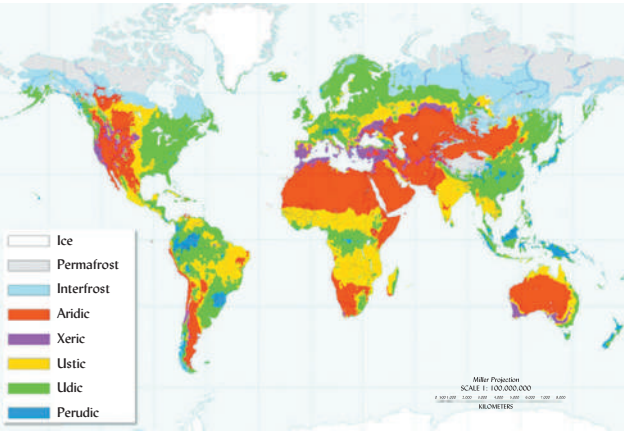


Figure 6.26 (Left) *Partitioning of liquid water losses (discharge) and vapor losses (evaporation and transpiration) in regions varying from low (arid) to high (humid) levels of annual precipitation. The example shown assumes that temperatures are constant across the regions of differing rainfall. Potential evapotranspiration (PET) is somewhat higher in the low-rainfall zones because the lower relative humidity there increases the vapor pressure gradient at a given temperature. Evaporation (E) represents a much greater proportion of total vapor losses (ET) in the drier regions due to sparse plant cover caused by interplant competition for water. The greater the gap between PET and ET, the greater the deficit and the more serious the water stress to which plants are subjected.* (Right) *The purple, yellow and especially red colors on the global map of soil moisture regimes indicate the regions of the world where water stress is most limiting to plant productivity on an annual basis. Only the blue and green areas in the map receive enough precipitation so that there is little or no gap between what the soil can offer and what the atmosphere demands in a year. See Section 3.2 for more information on soil moisture regimes.* (Diagram courtesy of Ray R. Weil, Map courtesy of USDA/NRCS)

For arable soils, the most effective practices aimed at controlling E are those that cover the soil. This cover can best be provided by mulches and by selected conservation tillage practices that leave plant residues on the soil surface, mimicking the soil cover of natural ecosystems.

Vegetative Mulches. A *mulch* is a material used to cover the soil surface primarily for the purpose of controlling evaporation, soil erosion, temperature, and/or weeds. Examples of *organic* mulches include straw, leaves, and crop residues. Mulches can be highly effective in checking evaporation, but they may be expensive and labor-intensive to produce or purchase, transport to the field, and apply to the soil. Mulching is therefore most practical for small

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areas (gardens and landscaping beds) and for high-value crops such as cut flowers, berries, fruit trees, and certain vegetables. It is much less labor-intensive to produce a mulch "in place" by growing a cover crop or cash crop and letting the residues remain on the soil surface (see Crop Residue and Conservation Tillage section, following).

In addition to reducing evaporation, vegetative mulches may provide these benefits: (1) reduce soil-borne diseases spread by splashing water; (2) provide a clean path for foot traffic; (3) reduce weed growth (if applied thickly); (4) moderate soil temperatures, especially preventing overheating in summer months (see Section 7.11); (5) increase water infiltration; (6) provide organic matter and, possibly, plant nutrients to the soil; (7) encourage earthworm populations; and (8) reduce soil erosion. Most of these ancillary benefits do *not* accrue from the use of plastic mulches, discussed next.

Plastic Mulches. Plastic films (and specially prepared paper) are also used as mulch to control evaporative water losses and warm the soil to encourage rapid early growth. If the plastic is opaque, the mulch can also help control weeds, eliminating the need for cultivation. High cost of plastic makes it practical only with the highest-value crops. The mulch is often applied by machine over raised soil beds, and plants grow through holes made in the film (Figure 6.27). These mulches are widely used for vegetable and small fruit crops and in landscaping beds, where they are often covered with a layer of tree-bark mulch or gravel for longer life and a more pleasing appearance. As long as the ground is covered, evaporation is checked, and in some cases remarkable increases in plant growth have been reported. Rainwater can usually infiltrate somewhat through the plant holes and in the uncovered interrow spaces, but irrigation tubes are often installed under the plastic. On the negative side, plastic mulches add no organic matter to soils and often encourage runoff and soil erosion between the mulched beds. Another major problem with plastic mulches is the difficulty of completely removing the plastic at the end of the growing season; after a number of years, scraps of plastic accumulate in the soil, causing an unsightly mess and interfering with water movement and cultivation. Properly disposing of or recycling dirty shredded plastic is also problematic. Some manufacturers now offer biodegradable and light-degradable plastic mulches (made from plant products) that remain intact for a month or so and then break down almost completely (see Figure 7.44).

Crop Residue and Conservation Tillage. We have seen that plant residues on the soil surface conserve soil moisture by reducing evaporation and increasing infiltration. *Conservation tillage* practices leave a high percentage of the residues from the previous crop on or near the surface. A conservation tillage practice widely used in subhumid and semiarid regions is

Figure 6.27 *For crops with high cash value, plastic mulches are commonly used. Red and black colored mulches are compared in an experimental field* (left). *Both colors control weeds, but the red plastic reflects red light up into the crop canopy encouraging rapid growth and flowering. A field of strawberries in California, USA* (right) *is grown with black plastic which encourages rapid crop growth, but also rapid chemical runoff and erosion.* (Photos courtesy of Ray R. Weil)

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stubble mulch tillage (Figure 6.28, *left*). With this method, residues such as wheat stubble or cornstalks from the previous crop are uniformly spread on the soil surface. The land is then tilled with special implements that permit much of the plant residue to remain on or near the surface. Conservation tillage planters are capable of planting through the stubble and allow much of it to remain on the surface during the establishment of the next crop. In semiarid regions, summer fallow is commonly combined with stubble mulching to conserve soil moisture. Unfortunately, plant growth in dry regions is usually insufficient to produce the large amount of residue mulches needed to greatly reduce evaporation and maximize water conservation (Table 6.2).

Other conservation tillage systems that leave residues on the soil surface include no-tillage (see Figure 6.28, *right*), where the new crop is planted directly into the sod or residues of the previous crop, with almost no soil disturbance (see also Figure 4.34). The long-term soil water conserving benefits of such tillage systems are shown in Box 6.1. Conservation tillage systems will receive further attention in Section 17.6.

Figure 6.28 *Conservation tillage leaves plant residues on the soil surface, reducing both evaporation losses and erosion.* (Left) *In a semiarid region (South Dakota, USA) the straw from the previous year's wheat crop was only partially buried to anchor it against the wind while still allowing it to cover much of the soil surface. In the next year the left half of the field, now shown growing wheat, will be* stubble mulched *and the right half sown to wheat.* (Right) No-till *planted corn in a more humid region grows up through the residues left on the surface by previous corn, soybean and wheat crops. Note that with no-till, virtually none of the soil surface is directly exposed to solar radiation, rain, or wind. Weeds are normally controlled with herbicide sprays.* (Photos courtesy of Ray R. Weil)

Table 6.2
GAINS IN SOIL WATER FROM DIFFERENT RATES OF STRAW MULCH DURING FALLOW PERIODS AT FOUR GREAT PLAINS LOCATIONS

Location	Mean annual precipitation, mm	Soil water gain, mm, at each mulch rate			
		0 Mg/ha	2.2 Mg/ha	4.4 Mg/ha	6.6 Mg/ha
Bushland (Texas, USA)	508	71	99	99	107
Akron (Colorado, USA)	476	134	150	165	185
North Platte (Nebraska, USA)	462	165	193	216	234
Sidney (Montana, USA)	379	53	69	94	102
Average		107	127	145	157
Average gain by mulching			20	38	50

From Greb (1983).

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6.5 LIQUID LOSSES OF WATER FROM THE SOIL

In our discussion of the hydrologic cycle we noted two types of liquid losses of water from soils: (1) water lost by percolation or drainage, and (2) water lost by surface runoff (see Figure 6.2). *Percolation water* recharges the groundwater and moves chemicals out of the soil. *Runoff water* often carries appreciable amounts of soil (erosion) as well as dissolved chemicals.

Percolation and Leaching

When the amount of rainfall entering a soil exceeds the water-holding capacity of the soil, losses by percolation will occur. Percolation losses are influenced by: (1) the amount of rainfall and its distribution, (2) runoff from the soil, (3) evaporation, (4) the character of the soil, and (5) the nature of the vegetation.

BOX 6.1

WATER CONSERVATION PAYS OFF

Productivity of grain crops per unit land area has increased dramatically around the world during the past few decades. Three major beneficial factors have stimulated these increases: (1) improved crop genetic potential (from plant breeding), (2) increased nutrient availability (mainly from fertilizers), and (3) increased amounts of available water (mostly from increased irrigation).

Figure 6.29 illustrates the contribution that conserved soil moisture has made to these yield increases, especially in semiarid areas of the United States. The sorghum grain yields from numerous plots at a USDA research facility in Lubbock, Texas, increased some 325%. over a 60-year period.

Further research suggests that about one-third of this yield increase could be attributed to improved varieties, the remaining two-thirds to other factors. Increased nutrient availability was ruled out as a yield-inducing factor since no fertilizers were applied to these plots.

This left increased water availability as the prime factor likely contributing to the higher yields. Analyses of rain and snowfall records showed no increase in precipitation that might have accounted for the increased yields. However, soil moisture measurements made at planting time (Figure 6.29, *right*) were found to be much higher during the period from 1972 to 1997 than in the earlier period (1956–1972).

Records showed that tillage and residue management were the primary factors that accounted for this soil moisture difference. During the earlier period (1956–1972) the plots were tilled between crops to control weeds, and little residue remained on the soil. During the later period (1972–1997) there was a major shift to no-tillage crop production, which maintained crop residues on the soil surface. Together with improved weed control using herbicides, the no-till systems reduced evaporative losses, leaving extra moisture in the soil to accommodate the increased sorghum yields.

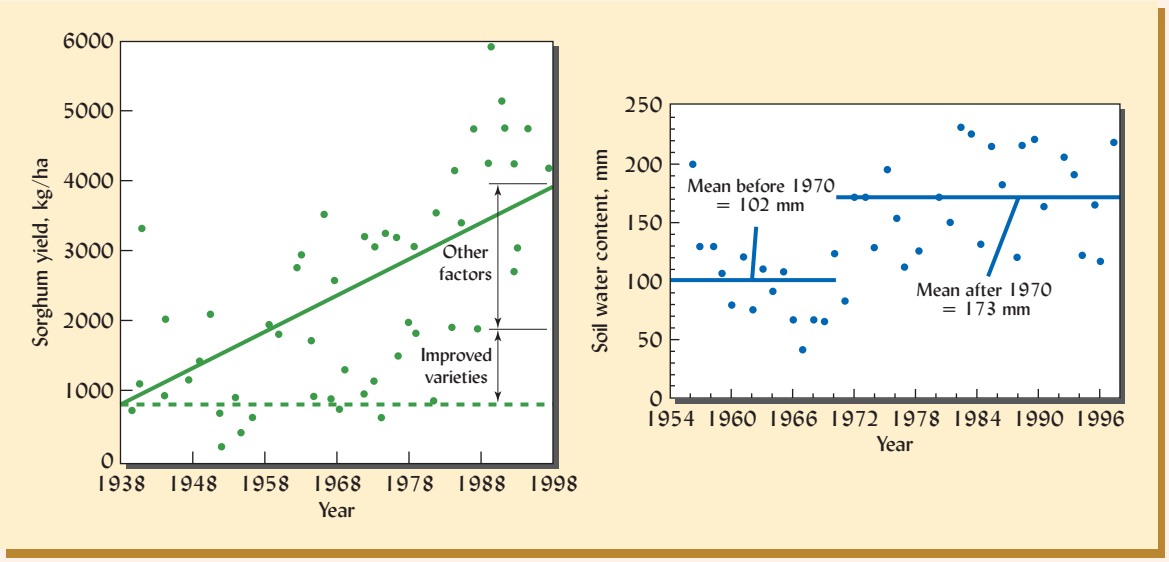

Figure 6.29 (Left) *Sorghum yield increases 1938 to 1998.* (Right) *Changes in soil water storage 1954 to 1997. From Unger and Baumhardt (1999).*

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Percolation–Evaporation Balance

Figure 6.30 illustrates the relationships among precipitation, runoff, soil storage, soil water depletion, and percolation for representative humid and semiarid temperate regions and for an irrigated arid region. In the humid temperate region, the rate of water infiltration into the soil (precipitation minus runoff) is greater, at least during certain seasons, than the rate of evapotranspiration. As soon as the soil field capacity is reached, percolation into the substrata occurs.

In the example shown in Figure 6.30*a*, maximum percolation occurs during the winter and early spring, when evaporation is lowest. During the summer, little percolation occurs. In fact, evapotranspiration exceeds precipitation, resulting in a depletion of soil water. Normal plant growth is possible only because of water stored in the soil from the previous winter and early spring.

In the semiarid region, as in the humid region, water is stored in the soil during the winter months and is used to meet the moisture deficit in the summer. But because of the low rainfall, little runoff and essentially no percolation out of the profile occur. Water may move to the lower horizons, but it is absorbed by plant roots and ultimately is lost by transpiration.

The irrigated soil in the arid region (Figure 6.30*c*) shows a unique pattern. Irrigation in the early spring, along with a little rainfall, provides more water than is being lost by evapotranspiration. The soil profile is charged with water, and some percolation may occur. As we shall see in Section 10.8, irrigation systems must provide enough water for some percolation, in order to remove excess soluble salts. During the summer, fall, and winter months, the stored water is depleted because the amount added is less than that removed by the very high evapotranspiration that takes place in response to large vapor pressure gradients.

The situations depicted in Figure 6.30 are typical of temperate zones where PET varies seasonally with temperature. In the tropics, where temperatures are somewhat higher and less variable, PET is somewhat more uniform throughout the year, although it does vary with seasonal changes in humidity. In very high rainfall tropical areas (perudic moisture regimes), much more runoff and somewhat more percolation occurs than shown in Figure 6.30. In irrigated areas of the arid tropics, the relationships are similar to those shown for arid temperate regions.

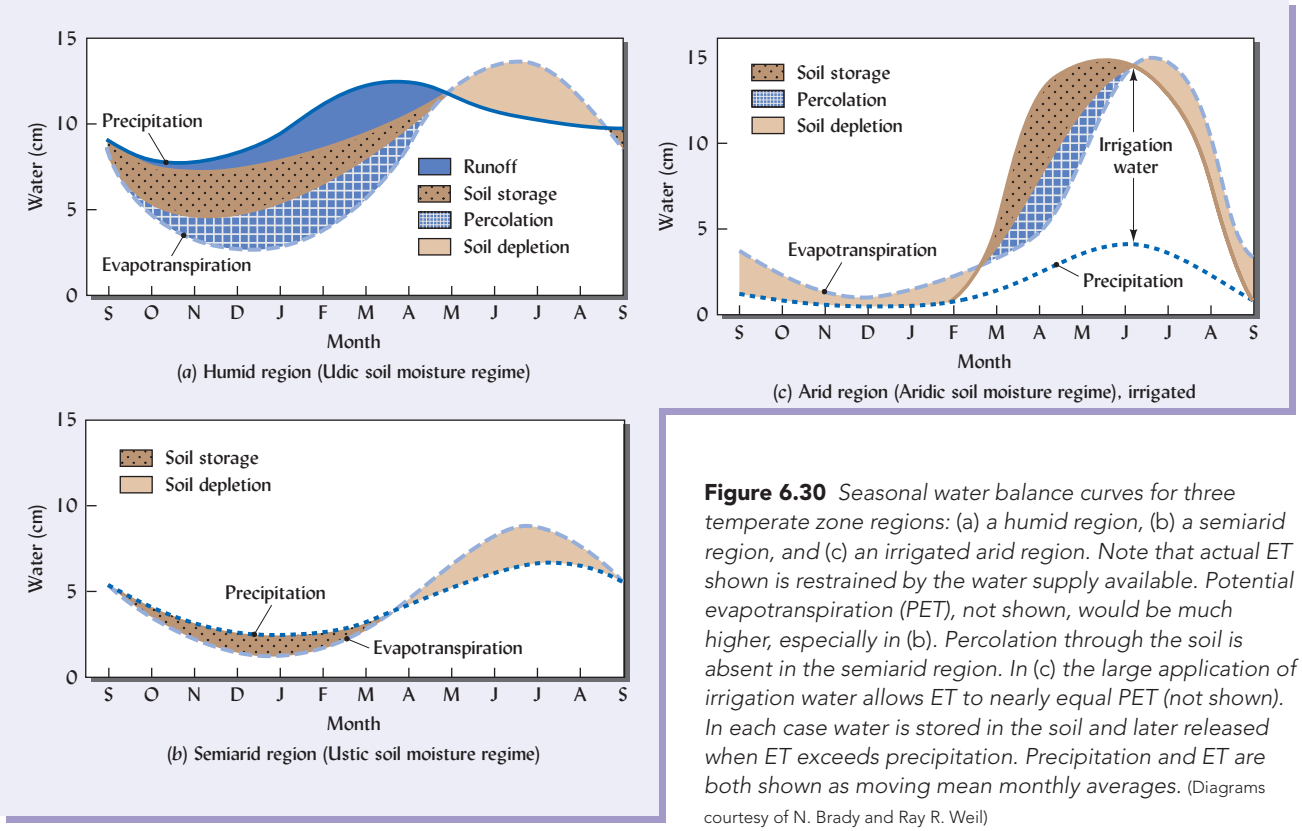

Figure 6.30 *Seasonal water balance curves for three temperate zone regions:* (a) *a humid region,* (b) *a semiarid region, and* (c) *an irrigated arid region. Note that actual ET shown is restrained by the water supply available. Potential evapotranspiration (PET), not shown, would be much higher, especially in* (b)*. Percolation through the soil is absent in the semiarid region. In* (c) *the large application of irrigation water allows ET to nearly equal PET (not shown). In each case water is stored in the soil and later released when ET exceeds precipitation. Precipitation and ET are both shown as moving mean monthly averages.* (Diagrams courtesy of N. Brady and Ray R. Weil)

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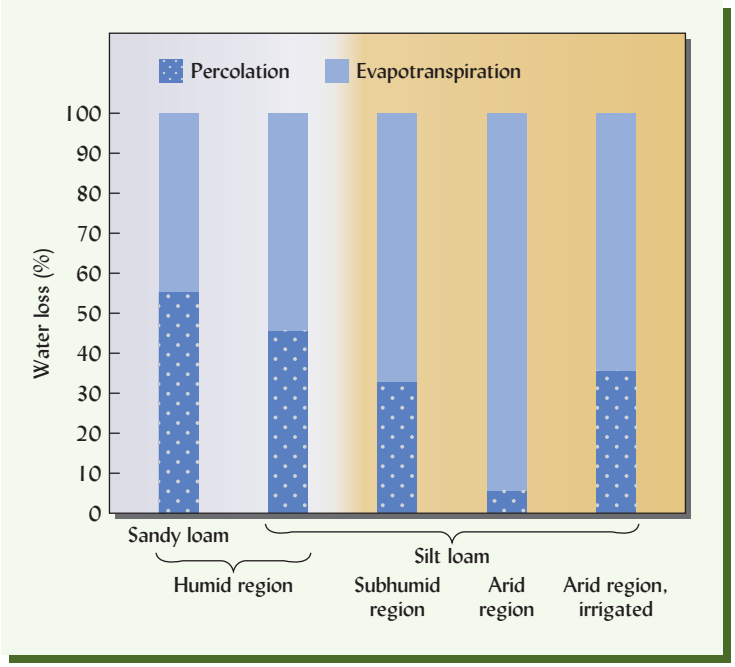

Figure 6.31 *Percentage of the water entering the soil that is lost by downward percolation and by evapotranspiration. Representative figures are shown for different climatic regions. The examples shown are for a nearly level terrain for which surface runoff can be assumed to be negligible.*

The comparative losses of water by evapotranspiration and percolation through soils found in different climatic regions are shown in Figure 6.31. These differences should be kept in mind while reading the following section on percolation and groundwaters.

6.6 PERCOLATION AND GROUNDWATER

When drainage water moves downward through the soil and regolith it eventually encounters a zone in which the pores are all saturated with water. Often this saturated zone lies above an impervious soil horizon (Figure 6.32) or a layer of impermeable rock or clay. The upper surface of this zone of saturation is known as the **water table**, and the water within the saturated zone is termed **groundwater**. The water table (Figure 6.33) is commonly only 1–10 m below the soil surface in humid regions but may be several hundred or even thousands of meters deep in arid regions. In swamps it is essentially at the land surface.

The unsaturated zone above the water table is termed the **vadose zone** (see Figures 6.32 and 6.33). The vadose zone may include unsaturated materials underlying the soil profile, and so may be considerably deeper than the soil itself. In some cases, however, the saturated zone may be sufficiently near the surface to include the lower soil horizons, with the vadose zone confined to the upper soil horizons.

Shallow groundwater receives downward-percolating drainage water. Most of the groundwater, in turn, seeps laterally through porous geological materials (termed **aquifers**) until it is discharged into springs and streams. Groundwater may also be removed by pumping for domestic and irrigation uses. The water table will move up or down in response to the balance between the amount of drainage water coming in through the soil and the amount lost through pumped wells and natural seepage to springs and streams. In humid temperate regions, the water table is usually highest in early spring following winter rains and snowmelt, but before evapotranspiration begins to withdraw the water stored in the soil above.

Groundwater Resources

Groundwater is a significant source of water for domestic, industrial, and agricultural use. For example, some 20% of all water used in the United States comes from groundwater sources, and about 50% of the people use groundwater to meet at least some of their needs. A shallow water-bearing layer that is not separated from the soil surface by any overlying impermeable layer is called an **unconfined aquifer**. Unconfined aquifers, which are replenished annually,

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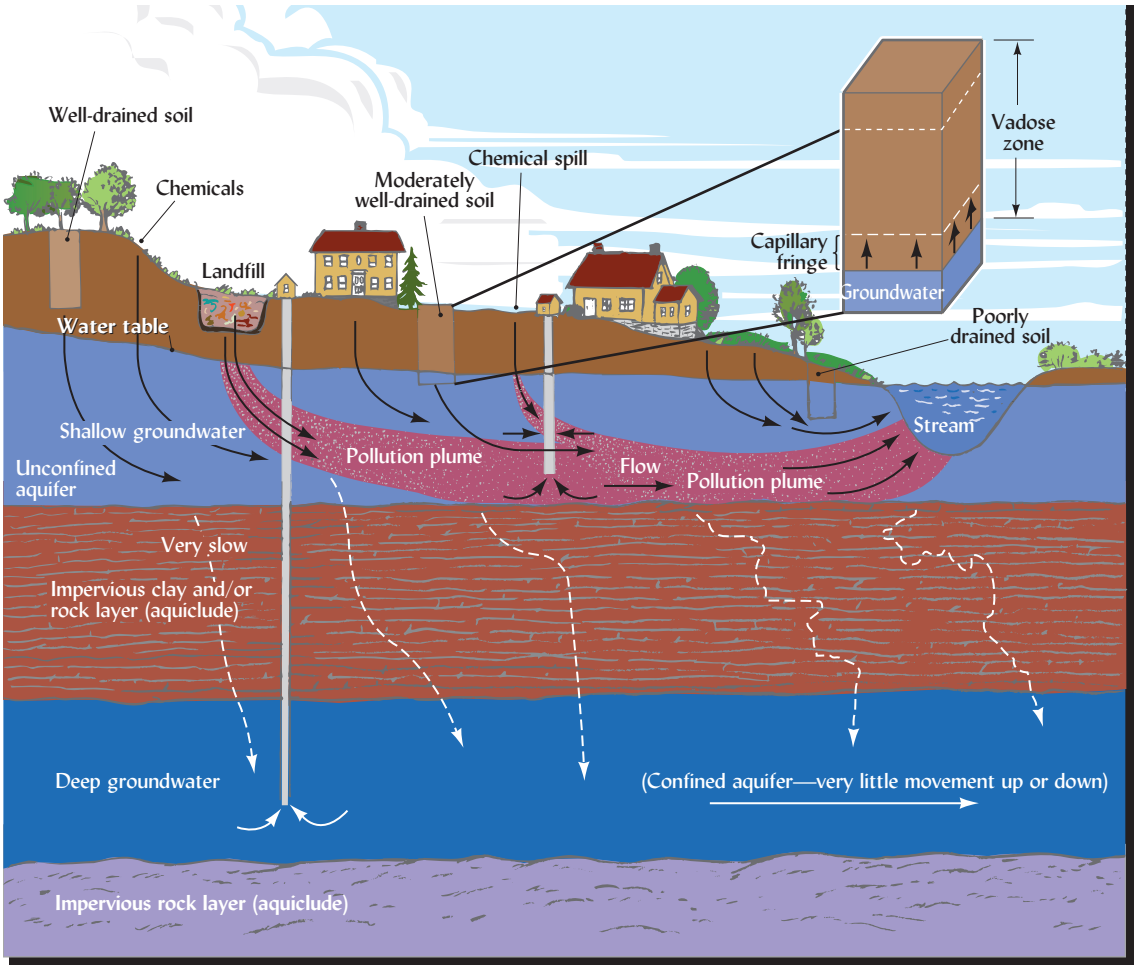

Figure 6.32 *The water table and groundwater in relation to water movement into and out of the soil. Precipitation and irrigation water percolate down the soil profile, ultimately reaching the water table and underlying shallow groundwater. The unsaturated zone above the water table is known as the* vadose zone (upper right). *Groundwater moves up from the water table by capillarity into the* capillary fringe. *Groundwater also moves horizontally down the slope toward a stream, carrying with it chemicals that have leached through the soil, including plant nutrients (N, P, Ca, etc.) as well as pesticides and other pollutants. A shallow well pumps groundwater from the unconfined aquifer near the surface. A deeper well extracts groundwater from a deep, confined aquifer. Two plumes of pollution are shown, one originating from landfill leachate, the other from a chemical spill. The former appears to be contaminating the shallow well.* (Diagram courtesy of Ray R. Weil)

commonly provide water for farm and rural dwellings (see Figure 6.32). The larger groundwater stores in deeper aquifers, which may take decades or centuries to recharge, are commonly pumped to meet municipal, industrial, and irrigation needs. In many cases deep wells are used to tap water from aquifers confined between impermeable strata (termed **aquicludes**). Water is replenished by slow, mainly horizontal seepage from **recharge areas** where the aquifer is exposed to the soil.

Water draining from soils is the main source of replenishment for most underground water resources. So long as water is not withdrawn faster than percolation allows it to be replenished, groundwater may be considered to be a renewable resource. However, in many areas of the world, people are pumping water out faster than it can be replenished, an activity that is lowering water tables and depleting the resource in a manner akin to mining an ore. When overpumping occurs in coastal areas, sea water may push its way into the aquifer, a process termed **saltwater intrusion** (as illustrated in Figure 6.2). Soon, deep municipal wells begin to pull in salty water instead of freshwater.

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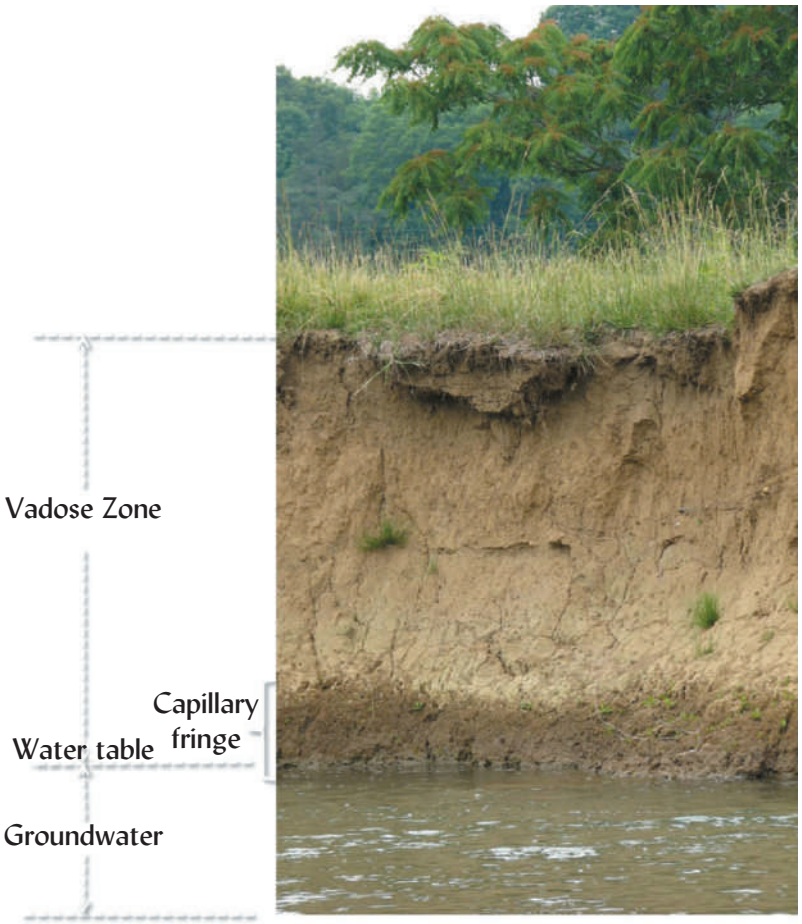

Figure 6.33 *The water table, capillary fringe, zone of unsaturated material above the water table (vadose zone), and groundwater are illustrated in this photograph. The groundwater can provide significant quantities of water for plant uptake.* (Photo courtesy of Ray R. Weil)

Shallow Groundwater

Groundwater that is near the surface can serve as a reciprocal water reservoir for the soil. Water removed from the soil by plants may be replaced by upward capillary movement from a shallow water table. The zone of wetting by capillary movement is known as the **capillary fringe** (see Figure 6.33). Such movement can provide a steady and significant supply of water that enables plants to survive during periods of low rainfall. However, capillary rise may also bring a steady supply of dissolved salts to the surface, a process that often leads to serious soil degradation in dry regions (see Section 10.3).

Movement of Chemicals in the Drainage Water[4]

Percolation of water through the soil to the water table not only replenishes the groundwater, it also dissolves and carries downward—or *leaches*—a variety of inorganic and organic chemicals found in the soil or on the land surface. Chemicals leached from the soil to the groundwater (and eventually to streams) in this manner include elements weathered from minerals, natural organic compounds resulting from decay or metabolism in the soil, plant nutrients derived from natural and human sources, and various synthetic chemicals applied intentionally or inadvertently to soils.

In the case of plant nutrients, especially nitrogen, downward movement through the soil and into underlying groundwater has at least three serious implications. First, the leaching of

[4]For a review of chemical transport through field soils, see Jury and Fluhler (1992).

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these chemicals represents a depletion of plant nutrients from the root zone (see Section 16.2). Second, accumulation of these chemical nutrients in ponds, lakes, reservoirs, and groundwater downstream may stimulate a process called *eutrophication*, which ultimately depletes the oxygen content of the water, with disastrous effects on fish and other aquatic life (see also Section 14.2). Third, in some areas underground sources of drinking water may become contaminated with excess nitrates to levels unsafe for human consumption (see Section 13.8).

Of even more concern is the contamination of groundwater with human pathogens (Box 6.2) and various toxic substances, such as pesticides, hormones, drugs, or chemicals leached out of waste disposal sites (see Chapter 18 for a detailed discussion of these pollution hazards). Figure 6.32 illustrates how groundwater can be charged with these contaminants, and how a plume of contamination can spread to downstream wells and bodies of water.

Chemical Movement Through Macropores

Studies of the movement of chemicals in soils and from soils into the groundwater and downstream bodies of water have called attention to the critical role played by large macropores in determining field hydraulic conductivity (see Section 5.5). The pore configuration in most soils is nonuniform. Old root channels, earthworm burrows, and clay shrinkage cracks commonly contribute large macropores that may provide channels for rapid water flow from the soil surface to depths of 1 m or more.

Once chemicals are carried below the zone of greatest root and microbial activity, they are less likely to be removed or degraded before being carried further down to the groundwater. This means that chemicals that are normally broken down in the soil by microorganisms

BOX 6.2

LEACHING OF CONTAMINANTS TO GROUNDWATER ENDANGERS HUMAN HEALTH

Chemical contaminants more readily leach into groundwater from some soils than from others. In homogeneous, fine-textured soils without preferential flow channels (such as shrinkage cracks or biopores) contaminants will move slowly enough within the top layers to allow most contaminants to be destroyed or removed from the water by interactions with the soil. By contrast, in excessively well-drained coarse-textured soils these contaminants move quickly through the soil horizons and down into the groundwater.

As we learned in Chapter 4, sandy soils have many large pores through which water percolates rapidly. As water percolates through a sandy soil it carries dissolved contaminants down to the water table, and then on to wetlands, streams, and underground aquifers, from which drinking water may be drawn. An unfortunate example of well-water contamination is found in the following story pieced from news reports.

Over a thousand people were sickened, and two died, from the 0157:H7 strain of *Escherichia coli*, which apparently had contaminated a shallow well used for drinking water at an annual fair in rural Washington County in New York, USA. Most *E. coli* bacteria are relatively harmless, but this particular strain can be deadly. An overflow crowd of 110,000 people attended the six-day fair. However, only those who consumed food and beverages from the western side of the 25-hectare fairgrounds on the final two days of the fair became ill. On this side, a shallow 7-m well was used as a source of water for the fire department and some 12 food vendors. The water system passed all tests conducted by state officials in June and just before the fair in August. However, the DNA of the bacteria in the well-water samples after the fair matched that of the bacteria in the victims.

Findings by Department of Health and by fair officials suggest that four main factors likely led to this tragic situation. First, a summer-long drought preceding the fair had lowered water tables below the inlet level of some shallow wells. Second, some 600 cattle that were shown at the fair were temporarily housed about 30 m from the well in question. Third, on the fourth day of the fair (August 26) a 5-cm rain soaked the area, including the manure-laden ground where the livestock were held. The fourth factor was the nature of the soil at the fairgrounds. The soil was a nearly level Hoosic gravelly sandy loam with a high sand content throughout the profile. This type of soil allows very rapid water percolation and possesses little capacity to remove contaminants by filtering or adsorption on clays.

These four factors allowed the *E. coli*–contaminated water from the cattle yard to percolate unpurified downward to the well's aquifer, raising its level so that shallow wells could pump out the contaminated water and sicken hundreds of people. Had the soil been more fine-textured, this sad event might well have been avoided. In any case, this incident reminds us of the need to take soil properties into consideration in managing the movement of pollutants in the environment.

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within a few weeks may move down through large macropores to the groundwater before their degradation can occur.

Preferential or Bypass Flow. In some cases, leaching of chemicals is most serious if the chemicals are merely applied on the soil surface. Chemicals may be washed from the soil surface into large pores, through which they can quickly move downward (Figure 6.34*a*,*c*). Research suggests that most of the water flowing through large macropores does not come into contact with the bulk of the soil. Such flow is sometimes termed **preferential** or **bypass flow**, as it tends to move rapidly around, rather than through, the soil matrix. As a result, if chemicals have been incorporated into the upper few centimeters of soil, their movement into the larger pores is reduced, and downward leaching is greatly curtailed (Figure 6.34*b*,*d*).

Intensity of Rain or Irrigation. During a high-intensity rainfall event, water and its dissolved chemicals move downward rapidly through channels and cracks (macropores), bypassing the bulk of the soil. In contrast, a gentle rain that in time may provide as much water as the more intense event would likely wet the upper soil aggregates thoroughly, thereby minimizing the rapid downward percolation of both water and the chemicals and pathogens it carries. Table 6.3 illustrates the effects of rainfall intensity on the leaching of pesticides applied to turfgrass.

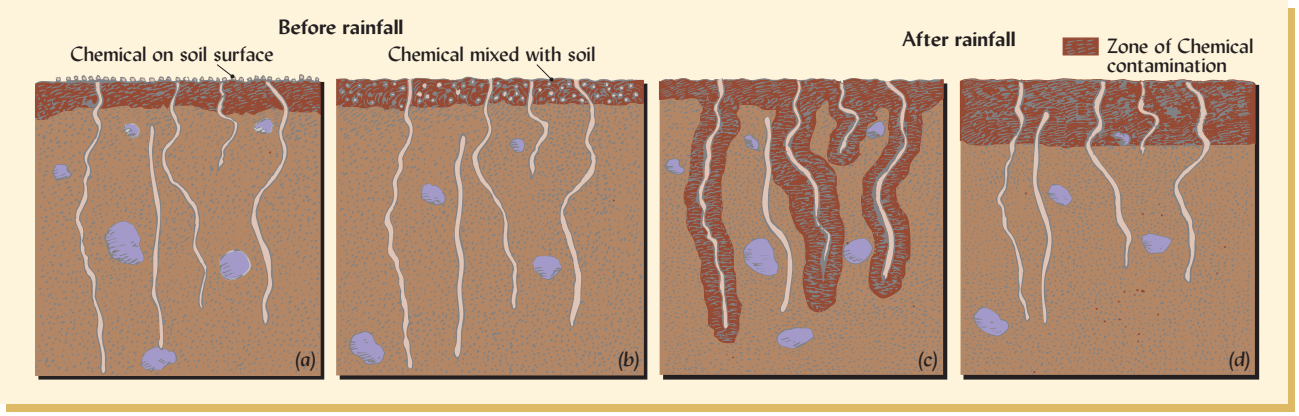

Figure 6.34 *Preferential or bypass flow in macropores transports soluble chemicals downward through a soil profile. Where the chemical is on the soil surface* (left) *and can dissolve in surface-ponded water when it rains, it may be transported rapidly down cracks, earthworm channels, and other macropores. Where the chemical is dispersed within the soil matrix in the upper horizon* (right), *most of the water moving down through the macropores will bypass the chemical, and thus little of the chemical will be carried downward. Note that channels* not *open all the way to the surface do not conduct water or contaminants by preferential flow.*

Table 6.3
INFLUENCE OF WATER APPLICATION INTENSITY ON THE LEACHING OF PESTICIDES THROUGH THE UPPER 50 CM OF A GRASS SOD–COVERED MOLLISOL

Soil columns with the natural structure undisturbed received heavy rain (four doses of 2.54 cm each) or light rain (16 doses of 0.64 cm each). Metalaxyl is far more water soluble than Isazofos, but in each case the heavy rain stimulated much more pesticide leaching through the macropores.

	Pesticide leached as percentage of that applied to surface	
Pesticide	**Heavy rains**	**Light rains**
Isazofos	8.8	3.4
Metalaxyl	23.8	13.9

Data from Starrett et al. (1996).

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Manipulations of soil macropores and irrigation intensity provide us with two examples of how environmental quality can be impacted by human activities that influence the hydrologic cycle. Likewise, we have considered steps that can be taken to influence the infiltration of water into soils and to maximize plant biomass production from the water stored in soils. The picture would not be complete if we did not consider briefly three other anthropogenic modifications to the hydrologic cycle: (1) the use of artificial drainage to enhance the downward percolation of excess water from some soils; conversely, (2) the application of wastewater to soils as a means of disposal, and (3) the use of irrigation to supplement water available for plant growth. We shall consider artificial drainage first.

6.7 ENHANCING SOIL DRAINAGE[5]

Some soils tend to be water-saturated in the upper part of their profile for extended periods during part or all of the year. In some soils, the prolonged saturation may be related to a low-lying landscape position, such that the regional water table is at or near the soil surface for extended periods. In other soils, water may accumulate above an impermeable layer in the soil profile, creating a ***perched water table*** (see Figure 6.35). Soils with either type of saturation may be components of wetlands, transitional ecosystems between land and water that are characterized by anaerobic (no oxygen) conditions (see Section 7.7).

Reasons for Enhancing Soil Drainage

Water-saturated, poorly aerated soil conditions are essential to the normal functioning of wetland ecosystems and to the survival of many wetland plant species. However, for most other land uses, these conditions are a distinct detriment.

Engineering Problems. During construction, the muddy, low-bearing-strength conditions of saturated soils make it very difficult to operate machinery (see Section 4.9). By the same token, soils used for recreation can withstand trampling much better if they are well drained. Houses built on poorly drained soils may suffer from uneven settling and flooded basements during wet periods. Similarly, a high water table will result in capillary rise of water into road-

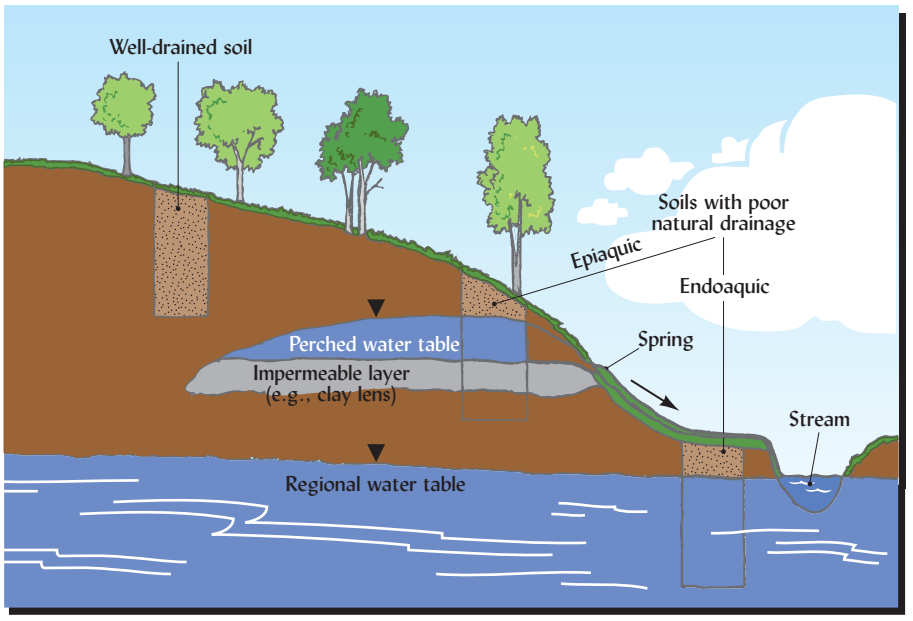

Figure 6.35 *Cross-section of a landscape showing the regional and perched water tables in relation to three soils, one well-drained and two with poor internal drainage. By convention, a triangle (▼) is used to identify the level of the water table. The soil containing the perched water table is wet in the upper part, but unsaturated below the impermeable layer, and therefore is said to be* epiaquic *(Greek* epi, upper*), while the soil saturated by the regional water table is said to be* endoaquic *(Greek* endo, within*). Artificial drainage can help to lower both types of water tables.* (Diagram courtesy of Ray R. Weil)

[5]For a review of all aspects of artificial drainage, see Skaggs and van Schilfgaarde (1999). For an update on controlled drainage for agriculture, see Skaggs et al. (2012).

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beds and around foundations, lowering the soil strength and leading to damage from frost-heaving (see Section 7.8) if the water freezes in winter. Heavy trucks traveling over a paved road underlain by a high water table create potholes and eventually destroy the pavement.

Plant Production. Water-saturated soils make the production of most upland crops and forest species difficult, if not impossible. In wet soil, farm equipment used for planting, tillage, or harvest operations may bog down. Except for a few specially adapted plant species (bald cypress trees, rice, cattails, etc.), most crop and forest species grow best in well-drained soils since their roots require adequate oxygen for respiration (see Section 7.1). Furthermore, a high water table early in the growing season will confine the plant roots to a shallow layer of partially aerated soil; the resulting restricted root system can lead to water stress later in the year, when the weather turns dry and the water table drops rapidly (Figure 6.36).

For these and other reasons, artificial drainage systems have been widely used to remove excess (gravitational) water and lower the water table in poorly drained soils. Land drainage is practiced in select areas in almost every climatic region, but is most widely used to enhance the agricultural productivity of clayey alluvial and lacustrine soils. Drainage systems are also a vital, if sometimes neglected, component of arid region irrigation systems, where they are needed to remove excess salts and prevent waterlogging (see Section 10.8). About 33% of the world's cropland requires drainage. Once the soils are drained, these lands are typically among the most productive of croplands.

Artificial drainage is a major alteration of the soil system, and the following potential beneficial and detrimental effects should be carefully considered. In many instances, laws designed to protect wetlands require that a special permit be obtained for the installation of a new artificial drainage system.

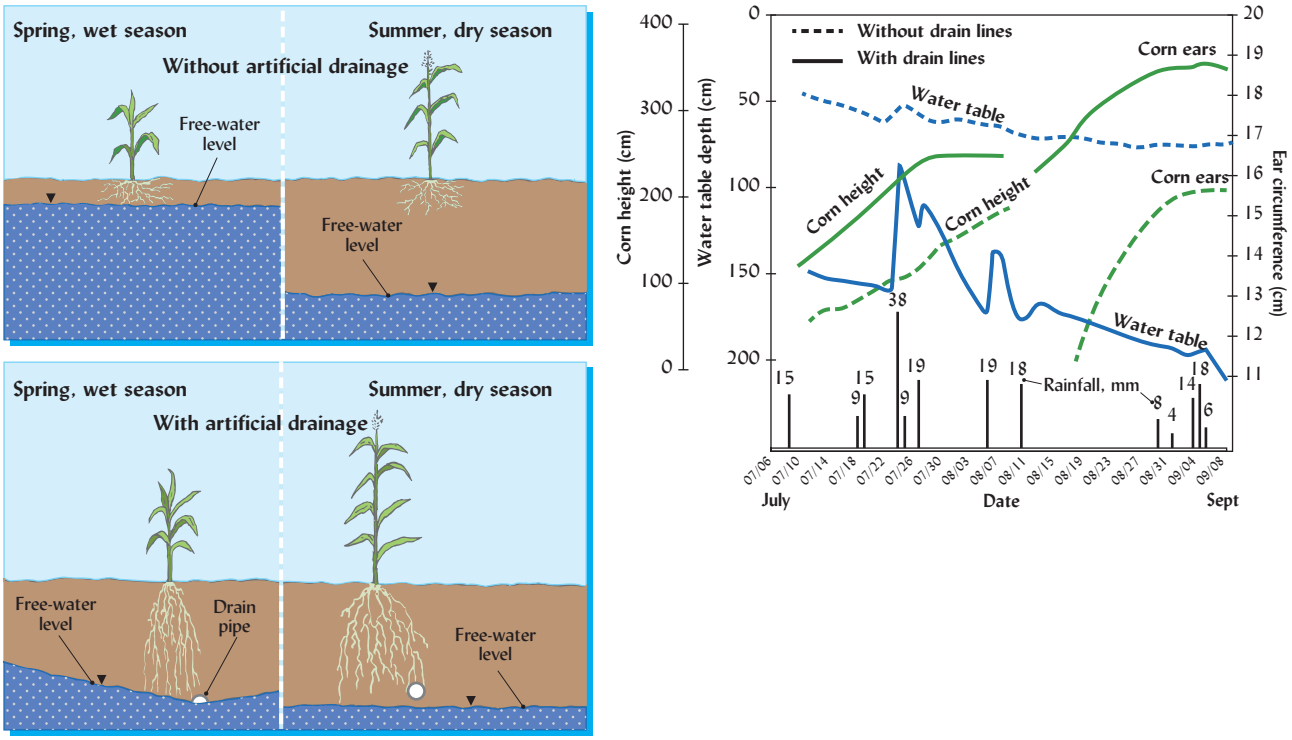

Figure 6.36 (Left) *Effects of artificial drainage on seasonal development of plant roots. The benefits of drainage include more vigorous early growth, as well as a more extensive root system capable of exploiting a larger volume of soil when the profile dries out in summer.* (Right) *Actual measurements of water table depth and corn growth (height and ear circumference) in two adjacent no-till fields in Wisconsin, USA, one with drain lines installed and one without drain lines. In the field without drain lines the water table dropped very slowly, remaining within 50–75 cm of the soil surface throughout the season. In the drained field, the water table dropped below 150 cm except during a rainy period in late July.* [Graph at *right* based on data in Kemper et al. (2012)]

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Benefits of Artificial Drainage

1. Increased bearing strength and improved soil workability, which allow more timely field operations and greater access to vehicular or foot traffic.
2. Less frost-heaving of foundations, pavements, and plants (e.g., see Figure 7.25).
3. Enhanced rooting depth, growth, and productivity of most upland plants due to improved oxygen supply and, in acid soils, lessened toxicity of manganese and iron (see Sections 7.3 and 7.5).
4. Reduced levels of fungal disease infestation in seeds and on young plants.
5. More rapid soil warming, resulting in earlier maturing crops (see Section 7.11).
6. Less production of methane and nitrogen gases that cause global environmental damages (see Sections 12.9 and 13.9).
7. Removal of excess salts from irrigated soils and prevention of salt accumulation by capillary rise in areas of salty groundwater (see Section 10.3).

Detrimental Effects of Artificial Drainage

1. Loss of wildlife habitat, especially waterfowl breeding and overwintering sites.
2. Reduction in nutrient assimilation and other biochemical functions of wetlands (see Section 7.7).
3. Increased leaching of nitrates and other contaminants to groundwater.
4. Accelerated loss of soil organic matter, leading to subsidence of certain soils (see Sections 3.9 and 12.8).
5. Increased frequency and severity of flooding due to loss of runoff water retention capacity.
6. Greater cost of damages when flooding occurs on alluvial lands developed after drainage.

Artificial drainage systems are designed to promote two general types of drainage: (1) *surface drainage* and (2) internal or *subsurface drainage*. Each will be discussed briefly.

Surface Drainage Systems

Surface drainage is extensively used, especially where the landscape is nearly level and soils are fine-textured with slow internal drainage (percolation). Its purpose is to remove water from the land before it infiltrates the soil.

Surface Drainage Ditches. Most surface drainage systems involve the construction of shallow ditches or swales with gentle side slopes that hasten runoff of surface water but do not interfere with equipment traffic. If there is some slope on the land, the shallow ditches are usually oriented across the slope and across the direction of planting and cultivating, thereby permitting the interception of water as it runs off down the slope. These ditches can be made at low cost with simple equipment. For removing surface water from landscaped lawns, this system of drainage can be modified by constructing gently sloping mounds and swales rather than ditches (Figure 6.37*a*).

Land Smoothing. Often, surface drainage ditches are combined with ***land smoothing*** to eliminate the ponding of water and facilitate its removal from the land. High spots are cut down and depressions are filled in (Figure 6.37*b*), often using precision laser–guided field-leveling equipment. The resulting land configuration permits excess water to move at a controlled rate over the soil surface to an outlet ditch and then on to a natural drainage channel. Land smoothing is also commonly used to prepare a field for flood irrigation (see Section 6.9).

Subsurface (Internal) Drainage

The purpose of subsurface drainage systems is to remove the groundwater from within the soil and to subsequently lower the water table (Figure 6.38). They require channels such as deep ditches, underground pipes, or "mole" tunnels into which excess water can flow. Internal drainage occurs only when the pathway for drainage is located below the level of the water table. The flow of water from a saturated soil into a drainage outlet is illustrated in Figure 6.39. Note that the water flowpath may first go down and then up toward the outlet pipe in response to potential gradients. In the same way, most groundwater enters a tile drain

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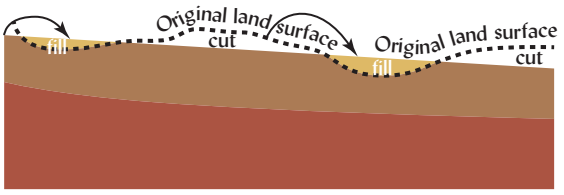
(a)

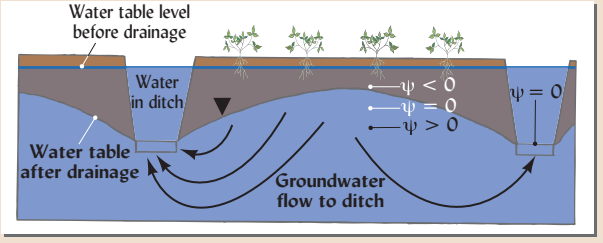


(b)

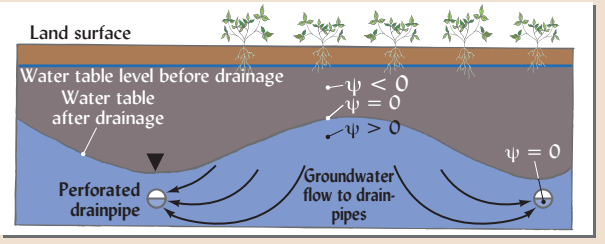
Figure 6.37 *Surface drainage encourages the removal of excess water by surface runoff before the water even enters the soil.* (a) *Gentle mounds are constructed to raise some soil farther above the shallow water table to improve aeration, while gentle swales are made to hasten the runoff of water before it infiltrates the soil.* (b) *Land leveling cuts down high spots and uses the cut material to fill in low spots, resulting in a smooth pathway for rapid surface water runoff with minimal ponding and waterlogging.* (Photo and diagram courtesy of Ray R. Weil)

(a)

(c)



(b)



(d)

Figure 6.38 *Two types of subsurface drainage system.* (a,b) *Open ditches are used to lower the water table in a poorly drained soil. The wet season levels of the water table before and after ditch installation are shown. The water table is deepest next to the ditch, and the drainage effect diminishes with distance from the ditch.* (c,d) *Buried "tile lines" made of perforated plastic pipe act very much as the ditches in* (a), *but have two advantages: they are not visible after installation and they do not present any obstacle for surface equipment. Note the flow lines indicating the paths taken by water moving to the drainage ditches or pipes in response to the water potential gradients between the submerged water* ($\omega > 0$) *and free water in the drainage ditch and pipes* ($\omega = 0$). (Diagrams and photos courtesy of Ray R. Weil)

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or a stream from the bottom. Box 6.3 provides an example of how knowledge of these basic principles of soil water movement and interaction with soil can be applied in designing a system to alleviate drainage problems in an ornamental garden.

Depending on the nature of the area to be drained, a network of drainage channels may be laid out in several types of patterns, ranging from a highly geometric series of parallel drain lines to a more random placement of few lines designed to drain specific low spots or intercept hillside seepage. Where the landscape is too level or at too low an elevation to provide for sufficient fall for gravity removal, expensive pumping operations are sometimes used to remove the drainage water (e.g., in parts the Netherlands and Florida, USA).

Deep Open-Ditch Drainage. If a ditch is excavated to a depth below the water table (Figure 6.38*a*,*b*), water will seep from the saturated soil, where it is under a positive pressure, into the ditch, where its potential will be essentially zero. Once in the ditch, the water can flow rapidly off the field, as it no longer must overcome the frictional forces that would delay its twisting journey through tiny soil pores. However, the ditches, being 1 m or more deep, present barriers to equipment. Therefore, deep-ditch drainage is generally practical only for sandy soils in which the high-saturated hydraulic conductivity ensures that the water table will be lowered for a considerable distance from each ditch and therefore the ditches may be placed far apart.[6] Open ditches need regular maintenance to control vegetation and sediment buildup.

Buried Perforated Pipes (Drain Tiles).[7] A network of perforated plastic pipes can be laid underground using specialized equipment (see Figure 6.38*c*). Water moves into the pipe through the perforations. The pipe should be laid with the slotted or perforated side *down*. This allows water to flow up into the pipe (as shown in Figure 6.39) but protects against soil falling into and clogging the pipe (see Figure 6.42*c*). Sediment buildup will also be avoided if the pipe has the proper slope (usually a 0.5–1% drop) so water flows rapidly to the outlet ditch or stream. A gate or wire mesh should cover the pipe outlet to prevent the entrance of rodents in dry weather but still allow the free flow of water.

If a control structure is installed at the outlet of a buried pipe (tile) drain network, the elevation of the outlet can be adjusted by raising or lowering an overflow barrier. This adjustment allows the manager to control the flow of water out of the system and the water table depth under the drained field. During the winter when root zone saturation is not a problem, the manager can restrict drainage flows and thus greatly reduce the loss of nutrients

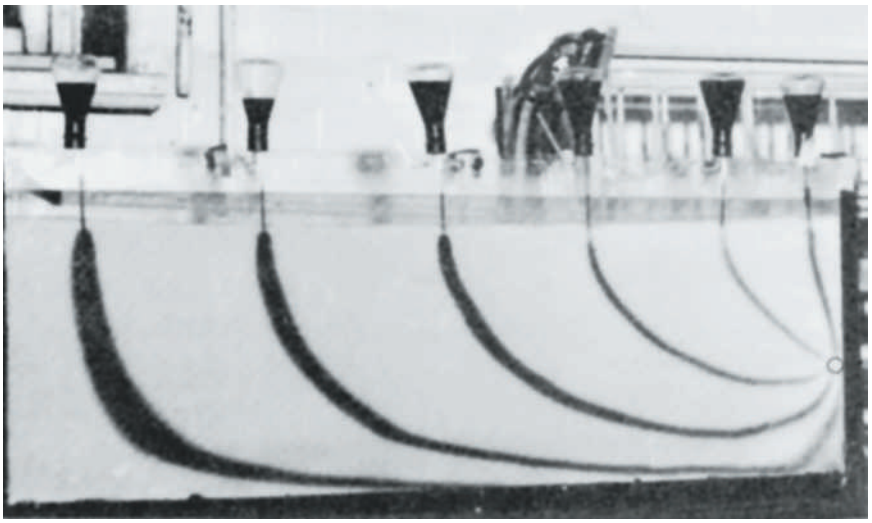

Figure 6.39 *Demonstration of the saturated flow patterns of water toward a drainage tile. Water containing a colored dye was added to the surface of the saturated soil, and drainage was allowed through a small pipe shown on the extreme right, simulating a drainage tile.* (George Stanley Taylor, Ohio State University Extension, outreach arm of the College of Food, Agricultural, and Environmental Sciences)

[6]The required spacing of ditches and buried drainpipes ranges from about 10 m apart for very low permeability soils to more than 100 m apart for high-permeability soils such as peats and sands.

[7]Before the adoption of plastic perforated pipe in the 1960s, short sections of ceramic pipe known as *tiles* were laid down end-to-end with small gaps between them through which water could enter. The terms *drain tile* or *tile line* are still often used in reference to the newer plastic pipe.

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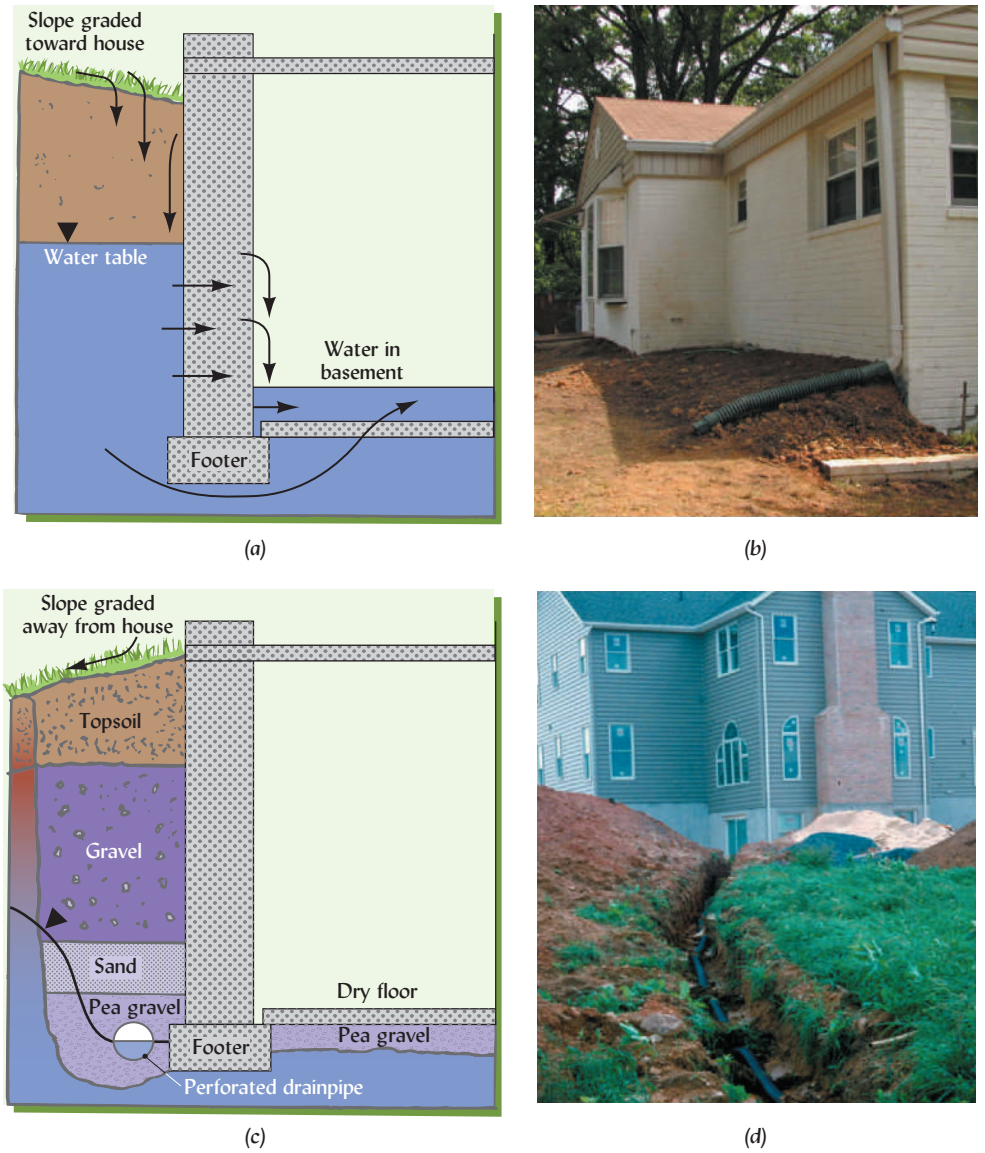

Figure 6.40 *The principles of water movement in soils are applied to protect foundations and keep basements dry.* (a) *The water table around a building foundation with poor drainage.* (b) *Measures that guide surface water away from the house foundation, including grading to make the soil surface slope away from the house and a black plastic drainpipe that extends the roof downspout away from the foundation.* (c) *Proper foundation drainage includes installation of a* footer drainpipe, *a layer of gravel between the concrete slab floor and the soil, and correct surface grading.* (d) *Photo showing installation of a footer drainpipe that carries water away from the bottom of the foundation, effectively lowering the water table to below the level of the basement floor. Soil will be back-filled to cover the foundation and black flexible drainpipe.* (Diagrams and photos courtesy of Ray R. Weil)

BOX 6.3

TOPIARY GARDEN SUCCESS HINGES ON DRAINAGE DESIGN

Dozens of hemlock trees, all carefully pruned into ornamental shapes (topiary) as part of an intricate landscape design, were dying again because of poor drainage. A very expensive effort to improve the drainage under the hemlocks had proved to be a failure, and the replanted hemlocks were again causing an unsightly blemish in an otherwise picture-perfect garden.

Finally, the landscape architect for the world-famous ornamental garden called in a soil scientist to assist her in finding a solution to the dying hemlock problem. Records showed that in the previous failed attempt to correct the drainage problem, contractors had removed all the hemlock trees in the hedge and had dug a trench under the hedge some 3 m deep (*a*). They had then backfilled the trench with gravel up to about 1 m from the soil surface, completing the backfill with a high-organic-matter, silt loam topsoil. It was into this silt loam that the new hemlock trees had been planted. Finally, a bark mulch layer had been applied to the surface.

The landscaper who had designed and installed the drainage system apparently had little understanding of the various soil horizons and their relation to the local hydrology. When the soil scientist examined the problem site, he found an impermeable claypan that was causing water from upslope areas to move laterally into the hemlock root zone (Figure 6.41*a*).

(continued)

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BOX 6.3

TOPIARY GARDEN SUCCESS HINGES ON DRAINAGE DESIGN *(CONTINUED)*

Basic principles of soil water movement could have predicted that water would not drain from the fine pores in the silt loam topsoil into the large pores of the gravel (compare the situation to that in Figures 5.26 and 5.28). In fact, the water moving laterally over the impermeable layer created a perched water table that poured water into the gravel-filled trench, soon saturating both the gravel and the silt loam topsoil.

To cure the problem, the previous "solution" had to be undone (*b*). The dead hemlocks were removed, the ditches were re-excavated, and the gravel was removed from the trenches. Then the trench, except for the upper ½ m, was filled with a sandy loam subsoil to provide a suitable rooting medium for the replacement evergreen trees (a different species was chosen for reasons unrelated to drainage). The upper ½ m of the trench was filled with a sandy loam topsoil, which was also acid but contained a higher level of organic matter. The interface between the subsoil and surface soil was mixed so that there would be no abrupt change in pore configuration. This would allow an unsaturated wetting front to move down from the upper to the lower layers, drawing down any excess water.

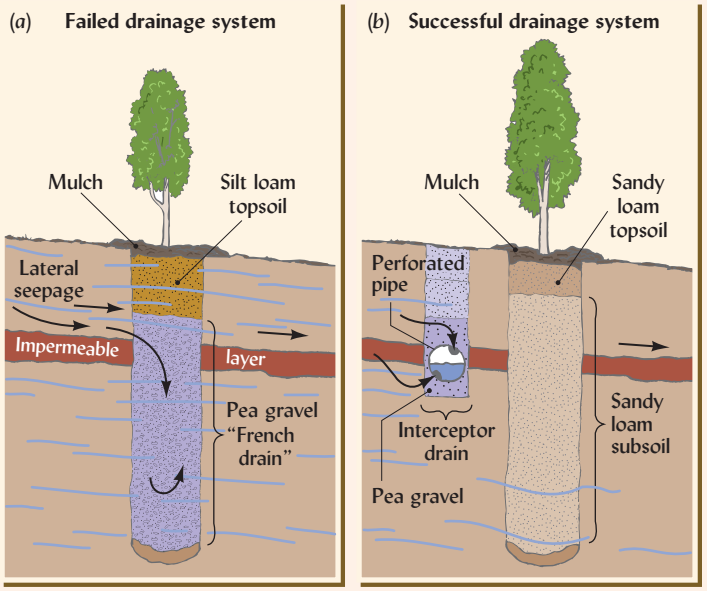

Figure 6.41 *Failed and successful drainage designs.* (Diagrams courtesy of Ray R. Weil)

About 1 m uphill from the tree planting a small trench was excavated through the impermeable clay layer that had been guiding water to the area. A perforated drainage pipe surrounded by a layer of gravel was laid in the bottom of this trench with about a 1% slope to allow water to flow away from the area to a suitable outlet. This *interceptor drain* prevented the water moving laterally over the impermeable soil layer from reaching the evergreen hedge root zone (Figure 6.41*b*).

Even though the replanting of the hedge was followed by an exceptionally rainy year, the new drainage system kept the soil well aerated, and the trees thrived. The principles of water movement explained in Sections 5.6 and 6.7 of this text were applied successfully in the field.

Figure 6.42 *Subsurface "tile" drainage systems.* (a) *Two outlet pipes empty drainage water from a tile drain system into an open ditch. Such an outlet is essential for a gravity drainage system to function.* (b) *Flexible plastic drainpipe perforated with holes on one side. These holes must be on the bottom of the drainpipe when it is installed, to avoid soil entering and clogging the pipe as shown in* (c), *where the pipe was installed with the holes on the top.* (Photos courtesy of Ray R. Weil)

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like nitrates to receiving waters. Lowering the barrier to increase drainage will enhance crop growth early in the season. Later in the season raising the barrier again can maintain a more shallow water table and conserve soil profile water for crop use during the relatively hot dry summer. Such managed drainage practices should be more widely adopted as they offer clear advantages for both productivity and environmental quality.

Building Foundation Drains. Surplus water around building foundations can cause serious damage. The removal of this excess water is commonly accomplished using buried perforated pipe, placed alongside and slightly below the foundation or underneath the floor (Figure 6.40*b*,*d*). The perforated pipe must be sloped to allow water to move rapidly to an outlet ditch or sewer. If the drain successfully prevents the water table from rising above the floor level, water will not seep into the basement for the same reason that it will not seep into a drainpipe placed above the water table.

Mole Drainage. A **mole drain** system can be created by pulling a pointed shank followed by an attached bullet-shaped steel plug about 7–10 cm in diameter through the soil at the desired depth. The compressed wall channel thus formed provides a pathway for the removal of excess water, similar to a buried pipe. Mole drainage is quite inexpensive to install, but is efficient only in fine-textured soils in which the channel is likely to remain open for a number of years.

6.8 SEPTIC TANK DRAIN FIELDS

Many ordinary suburbanites get their first exposure to the importance of water movement through soils when they apply for a permit to build their new dream house. The local authorities will usually not allow a home to be built until arrangements are made for wastewater treatment. Typically, a soil scientist will come out to inspect the soils at the homesite and judge their suitability for use as a septic tank **drain field**. If the soils are found unsuitable, the landowner may be denied the permit to build.

Thus, in many regions, it is through their wastewater treatment function that soil properties influence the value of land and the spread of residential development. For consulting soil scientists in industrialized nations, determination of soil suitability for septic tank drain fields is probably the single most commonly rendered service. Furthermore, in rapidly suburbanizing areas improperly sited septic tank drain fields may contribute significantly to pollution of groundwater and streams. For all these reasons, our discussion of practical water management in soil systems would be incomplete without consideration of the soils in on-site wastewater treatment in areas not served by a centralized sewage treatment system.

Operation of a Septic System

The most common type of on-site wastewater treatment for homes not connected to municipal sewage systems is the *septic tank* and associated *drain field* (sometimes called *filter field* or *absorption field*). This method of sewage and wastewater treatment depends on several soil processes, of which the most fundamental is the movement of water through the soil.

In essence, a septic drain field operates like artificial soil drainage in reverse (Figure 6.43). A network of perforated underground pipes is laid in trenches, very much like the network of drainage pipes used to lower the water table in a poorly drained soil. But instead of draining water away from the soil, the pipes in a septic drain field carry wastewater *to* the soil, the water entering the soil via slits or perforations in the pipes. In a properly functioning septic drain field, the wastewater will enter the soil and percolate downward, undergoing several purifying processes before it reaches the groundwater. One of the advantages of this method of sewage treatment is that it has the potential to replenish local groundwater supplies for other uses.

The Septic Tank. Water carrying wastes from toilets, sinks, and bathtubs flows by gravity through sealed pipes to a large underground concrete box, called the *septic tank* (Figure 6.43*b*). Baffles in the tank cause the inflowing wastewater to slow down and drop most (70%) of its load of suspended solid materials, which subsequently settle to the bottom of the septic tank. As the organic solids partially decompose by microbial action in the septic tank, their volume

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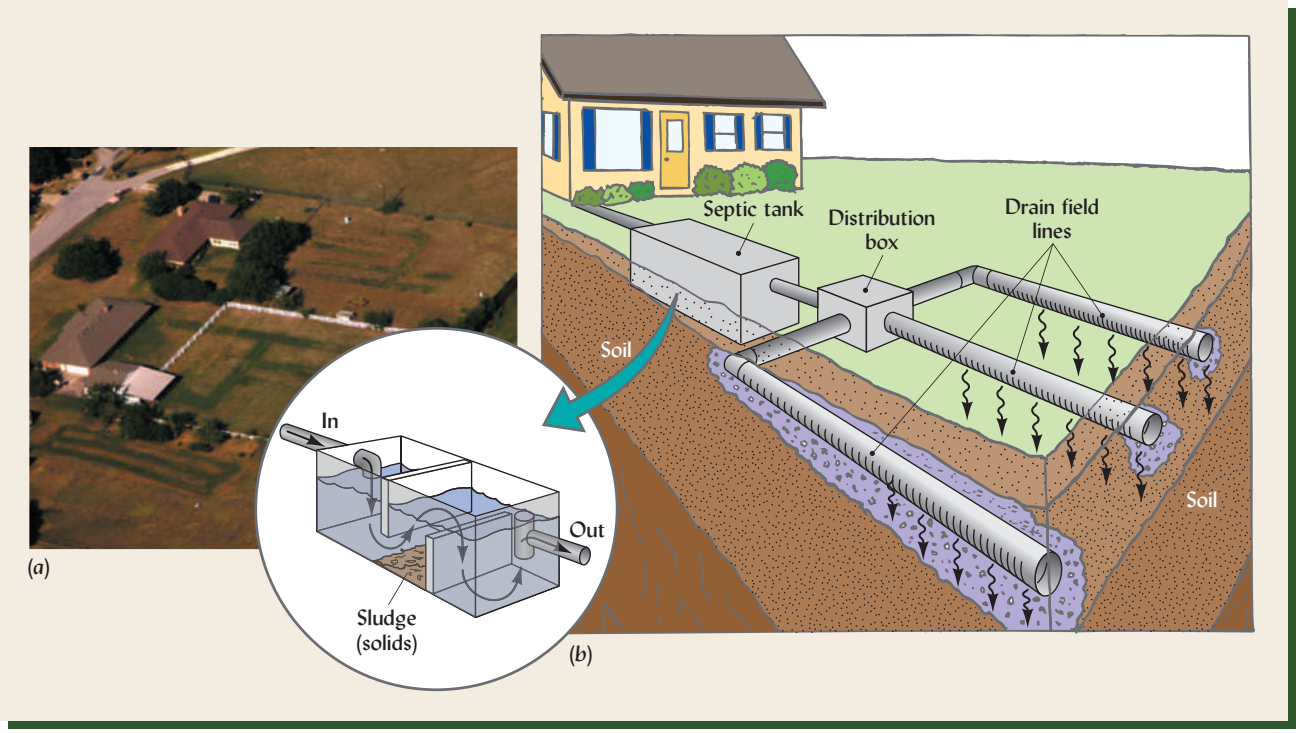

Figure 6.43 *On-site wastewater treatment with a soil-based septic drain field system.* (a) *During dry weather the lawn grasses around houses in Texas, USA, exhibit darker green bands where the grass is responding to water and nutrients released by underground septic drain field lines.* (b) *A diagrammatic representation of a septic system showing the main parts, including three drain field lines made from perforated pipe embedded in gravel at the bottom of trenches. The wastewater trickles from theses pipes into the native soil for purification. The inset diagram shows a cut-away view of the septic tank which traps most of the solids in the waste stream.* (Photo and diagram courtesy of Ray R. Weil)

is reduced so that many years may pass before the septic tank becomes too full and the accumulated **sludge** (also called *septage*) has to be pumped out. Because these systems depend on active microorganisms and have limited physical storage capacities, one should avoid introducing harmful chemicals or nonbiodegradable materials.

The Drain Field. The water exiting the septic tank via a pipe near the top is termed the septic tank **effluent**. Although its load of suspended solids has been much reduced, it still carries organic particles, dissolved chemicals (including nitrogen), and microorganisms (including pathogens). The flow is directed to one or more buried pipes that constitute the **drain field**. Blanketed in gravel and buried in trenches about 0.6–2 m under the soil surface, these pipes are perforated on the bottom to allow the wastewater to seep out and enter the soil. It is at this point that soil properties play a crucial role. Septic systems depend on the soil in the drain field to: (1) keep the effluent out of sight and out of contact with people, (2) treat or purify the effluent, and (3) conduct the purified effluent to the groundwater.

As the wastewater percolates, soil microbial action removes the organic materials and pathogens, but releases nitrates that are subject to leaching into the groundwater. Some 4–5 kg of nitrogen per year per person using the system may be released in this manner. This suggests that septic tanks from a group of family homes in near proximity to each other may release to the groundwater sufficient nitrates to be of environmental concern.

Soil Properties Influencing Suitability for a Septic Drain Field

The soil should have a *saturated hydraulic conductivity* (see Section 5.5) that will allow the wastewater to enter and pass through the soil profile rapidly enough to avoid backups that might saturate the surface soil with effluent, but slowly enough to allow the soil to purify the effluent

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before it reaches the groundwater. The soil should be sufficiently *well aerated* to encourage *microbial breakdown* of the wastes and *destruction of pathogens*. The soil should have some fine pores and clay or organic matter to adsorb and filter contaminants from the wastewater.

Soil properties that may disqualify a site for use as a septic drain field include impermeable layers such as a fragipan or a heavy claypan, gleying in the upper horizons indicating extended saturated conditions, too steep a slope, or excessively drained sand and gravel.

Septic tank drain fields installed where soil properties are not appropriate may result in extensive pollution of groundwater and in health hazards caused by seepage of untreated wastewater. In Figure 6.43*a* the dark green lines in the lawn show where the grass has responded to the water and nitrogen in the waste stream. Such signs indicate that the soil has too slow a percolation rate or too high a water table and that the wastewater has moved upward rather than downward.

Suitability Rating. The suitability of a site for septic drain field installation depends largely on soil properties that affect water movement and the ease of installation (see Table 6.4). For example, too steep a slope may interfere both with the ease of installation and with the operation of a septic drain field. A septic drain field laid out on a slope greater than 15% may allow considerable lateral movement of the percolating water such that at some point downslope, the wastewater will seep to the surface and present a potential health hazard.

The soil properties ideal for a septic drain field are nearly the opposite of those associated with the need for tile drainage. For example, instead of a high water table that requires lowering by drainage, septic drain field sites should have a low water table so that there is plenty of well-aerated soil to purify the wastewater before it reaches the groundwater. Application of large quantities of wastewater through septic drain fields will actually raise the water table somewhat under the drain field.

Perc Test. This is a test that determines the *percolation rate* (which is related to the saturated hydraulic conductivity described in Section 5.5) expressed in millimeters (or other unit of depth) of water entering the soil per hour. The percolation rate indicates whether or not the soil can accept wastewater rapidly enough to provide a practical disposal medium (Table 6.4). The test is simple to conduct (Figure 6.44) and should be carried out during the wettest season of the year.

To some degree, a low percolation rate can be compensated for by increasing the total length of drain field pipes, and hence increasing the area of land devoted to the drain field. The

Table 6.4
SOIL PROPERTIES INFLUENCING SUITABILITY FOR A SEPTIC TANK DRAIN FIELD
Note that most of these soil properties pertain to the movement of water through the soil profile.

	Limitations		
Soil property[a]	**Slight**	**Moderate**	**Severe**
Flooding	—	—	Floods frequent to occasional
Depth to bedrock or impermeable pan, cm	>183	102–183	<102
Ponding of water	No	No	Yes
Depth to seasonal high water table, cm	>183	122–183	<122
Permeability (perc test) at 60–152 cm soil depth, mm/h	50–150	15–50	<15 or >150[b]
Slope of land, %	<8	8–15	>15
Stones >7.6 cm, % of dry soil by weight	<25	25–50	>50

[a]Assumes soil does not contain permafrost and has not subsided more than 60 cm.
[b]Soil permeability (as determined by a perc test) greater than 150 mm/h is considered too fast to allow for sufficient filtering and treatment of wastes.
Adapted from Soil Survey Staff (1993), Table 620–17.

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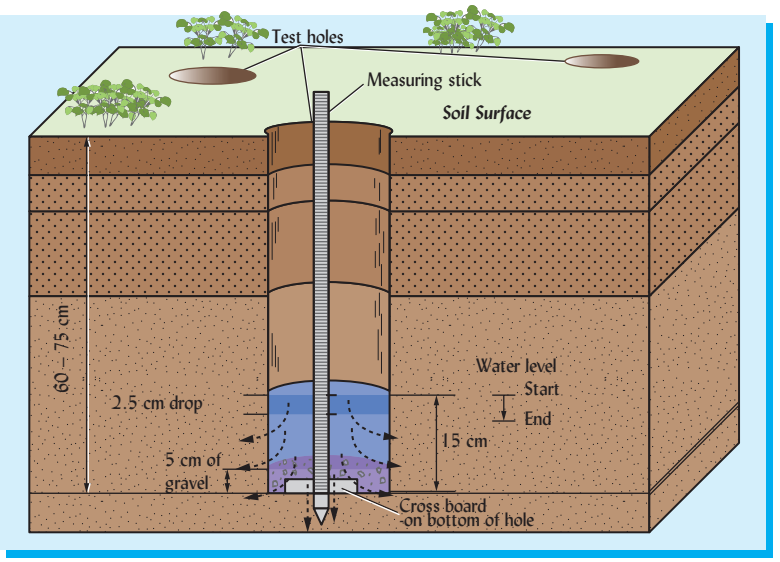

Figure 6.44 *The perc test used to help determine soil suitability for a septic tank drain field. On the site proposed for the drain field, a number of holes are drilled to the depth where the perforated pipes are to be laid. The bottom of each hole is lined with a few centimeters of gravel, and the holes are filled with water as a pretreatment to ensure that the soil is wet when the test is conducted. After the water has drained, the hole is refilled with water and a measuring rod is used to determine how rapidly the water level drops during a period of several hours or a day. This measurement is related to the saturated hydraulic conductivity.* (Diagram courtesy of Ray R. Weil)

Figure 6.45 *A mound-type septic tank effluent treatment system installed for an historic house in a flat, poorly drained region where the shallow water table precludes the burial of septic drain lines in conventional deep ditches. Note the white air vent pipe at the foot of the mound in the foreground.* (Photo courtesy of Ray R. Weil)

size of the septic drain field is also influenced by the amount of wastewater that is likely to be generated (which may be estimated by the number of bedrooms in the house being served).

Alternative Systems

In certain low-lying regions, it is virtually impossible to find sites where the water table is deep enough to be suitable for installation of a standard septic tank drain field. When this is the case, alternatives to the traditional underground septic drain field must be found.

One of these alternatives is the *mound drain field system*, which involves the construction of a septic drain field above ground (Figure 6.45). The perforated drain field pipes are laid above ground on a bed of sand and are covered by a mound of sandy soil material. A final covering of loamy soil is used to support grass vegetation. This type of system must rely on pumps to deliver the wastewater up to the perforated pipes in the mound. Vegetation established on the mound will use some of the water for evapotranspiration, but most of the wastewater will seep through the porous mound material into the underlying soil.

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A few communities are experimenting with artificial wetlands constructed to treat septic tank effluent where soils are too impermeable or low-lying to be suitable for a standard drain field. The effluent is made to slowly flow through a series of shallow, vegetated ponds that purify the wastewater by physically filtering some of the solids and by removing or destroying nutrients and organic compounds by plant uptake and biochemical reactions.

Such alternatives to septic drain fields require a special permit and are not allowed in all localities. Still more uncommon, but more environment friendly, are self-contained composting toilets that convert human wastes directly into a humuslike soil amendment rather than using water to flush wastes away into the soil. As discussed in Sections 16.5 and Box 20.2, compost toilets and other systems that allow for actually recycling the nutrients in human wastes will be required for our long-term sustainability on Earth.

6.9 IRRIGATION PRINCIPLES AND PRACTICES[8]

While an adult human requires about 2–4 liters of water for drinking each day, it requires some 3000–7000 liters of water to grow the food eaten by that person in a day. This water requirement includes the use of both "green" water and "blue" water resources (Table 6.6). In Sections 6.2–6.6 we focused primarily on effective management of green water resources—natural precipitation water stored in the soil profile for plant uptake. In irrigated agriculture, this green water is supplemented by the application of blue water resource – water withdrawn from lakes, rivers, or underground aquifers.

In most regions of the world, insufficient water is the prime limitation to agricultural productivity. In semiarid and arid regions, intensive crop production is all but impossible without supplementing the meager rainfall provided by nature. However, if given supplemental water through irrigation, the sunny skies and fertile soils of some arid regions stimulate extremely high crop yields. It is no wonder, then, that many of the earliest civilizations depended on irrigated agriculture (and vice versa). The history of irrigation is nearly as old as the history of agriculture itself. Rice producers in Asia, wheat and barley producers in the Middle East, and corn producers in Central and South America were irrigating their crops well over 2000 years ago. The ancient Mesopotamian civilizations of the Tigris and Euphrates river valleys created complex networks of canals and ditches to divert water from the great rivers to extensive areas of cultivated land. In other places, farmers filled simple buckets with water from a stream or open well and carried it to the thirsty plants in their gardens. Today these methods of water conveyance can still be seen, although in many agricultural and landscaping systems they have been replaced by modern pumps and pipes.

Importance of Irrigation Today

Food Production. During the twentieth century, the area of irrigated cropland expanded greatly in many parts of the world. However, in recent decades, the total area under irrigation seems to be leveling off at about 275 million hectares worldwide (see Figure 20.16). Application of irrigation water typically increases the productivity of the land by 100%–400%, accounting for the fact that the 20% of cropland that is irrigated produces about 40% of the world's crop yield.

Expanded and improved irrigation, especially in Asia, has been a major factor in helping global food supplies keep up with, and even surpass, the global growth in population. As a result, agricultural irrigation remains the largest *consumptive* use of water resources, accounting for about 80% of all water consumed worldwide, in both developing and developed countries (Figure 6.46). Water withdrawn for irrigation and lost to the atmosphere by evapotranspiration is a consumptive use, but water withdrawn to cool an electric generation turbine and then returned to the river from which it came is a nonconsumptive use (Table 6.5). On average,

[8]For a fascinating account of water resources and irrigation management in the Middle East, see Hillel (1995). For a practical manual on small-scale irrigation with simple but efficient microtechnology, see Hillel (1997). For extensive information on methods of irrigating crops, see Lascano and Sojka (2007). For perspectives on optimal irrigation and crop management when water supply is either scarce enough to be fixed or plentiful enough to be nonlimiting, see Basso and Ritchie (2012).

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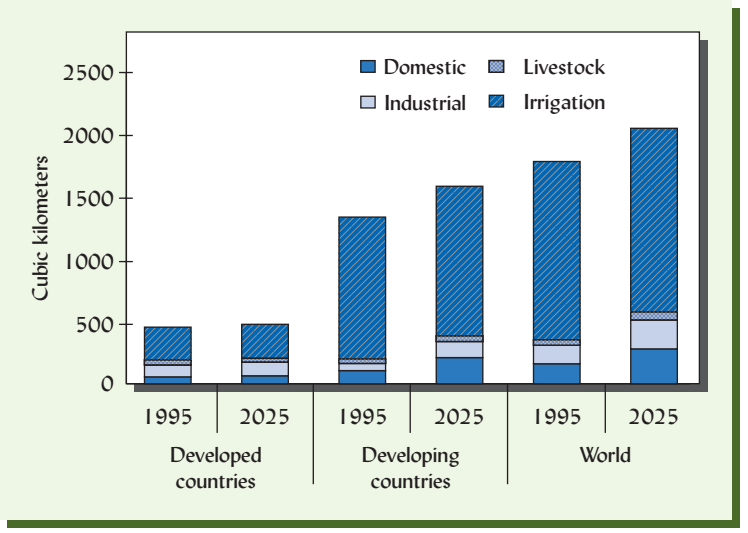

Figure 6.46 *Consumptive use of water for domestic, industrial, livestock, and irrigation purposes in developing and developed countries and for the world. Consumptive use refers to water that is withdrawn by pumping from rivers or aquifers but not returned to the source after use. Most of it eventually evaporates. The values for 2025 are predicted. Note that irrigation is the dominant consumer of water in all cases.* [From Rosegrant et al. (2002). Reproduced and adapted with permission from the International Food Policy Research Institute and the International Water Management Institute]

Table 6.5
SOME TERMS USED TO DESCRIBE VARIOUS POOLS AND USES OF THE WATER RESOURCE

Water term	Explanation
Blue water	Freshwater available for removal from surface water bodies (rivers, lakes) and aquifers.
Green water	Water stored in the soil as soil moisture and used by plants in evapotranspiration.
Gray water	Mildly contaminated waste water from industrial or municipal uses that can safely be reused for nonpotable purposes such as irrigation or flushing toilets.
Black water	Waste water that has been contaminated with human wastes and is unsafe to reuse or discharge into streams without extensive treatment.
Irrigation water	Blue water consumed by the production of plants (crops, lawns, etc.).
Water withdrawals	Water removal for use from surface water bodies or subsurface aquifers.
Nonconsumptive water use	Water returned to any freshwater source after its use and available for further use.
Consumptive water use	Freshwater withdrawals which are not immediately available for further use because they have been evaporated, embodied in products and waste, or discharged after use into different watersheds or the sea.
Water degradation	Water which is discharged in the same watershed from which it was withdrawn, but after the quality of water has been compromised.

about 30–35% of the water withdrawals for irrigation are returned to water sources for reuse and are not part of the consumptive use. By contrast, 90–95% of the withdrawals for industrial use are returned to the same watershed and so are not considered consumptive use.

Landscaping. Irrigation is an integral part of such landscaping installations as golf courses, flower beds, municipal parks, and home lawns (see Figure 6.6). Irrigation serves to keep the grass green during summer dry spells in humid regions, but is necessary almost year-round to keep certain species thriving in drier regions. In arid regions, irrigation can alter a glaring, brown landscape into one of cooling shade trees and colorful flowers. In most cases, the use of irrigation for landscaping is predicated on the desire to maintain vegetation that conforms to an ideal notion of perpetual green lushness. For example, in the United States, turfgrass species such as Kentucky bluegrass, which is naturally verdant in Kentucky only during a few cool, wet months, are made to stay green year-round in some desert gardens.

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In contrast, lawns, landscapes, and golf courses in many parts of the world utilize only adapted vegetation that is capable of surviving the periods of dry weather and other adverse conditions characteristic of the local climate without irrigation. Increasing environmental awareness has engendered a growing trend toward more xerophytic landscaping (utilizing desert plants and rocks) in arid regions and generally toward more use of locally native vegetation that requires little or no irrigation.

Future Prospects. The water for expanded irrigation has come largely from reservoirs formed by the construction of dams and from the pumping of groundwater out of deep aquifers. Among the problems facing irrigated agriculture in the future is the slowly dwindling availability of irrigation water from both of these sources. The reasons for reduction include: (1) increased competition for water from a growing population of urban water users, (2) the overpumping of aquifers that has led to falling water tables, (3) reduction of storage capacity of existing reservoirs by siltation with eroded sediments (see Section 17.2), and (4) increased recognition of the need to allow a portion of river flows to go unused by irrigation in order to maintain fish habitats downstream. Water resources for irrigation are most rapidly becoming scarce and/or expensive in arid regions where they are most needed. Reducing waste and achieving greater efficiency of water use in irrigation are increasingly important aspects that will be emphasized in this section. One of the other major problems associated with irrigation, the salinization of soils and drainage waters, is considered in Chapter 10.

Water-Use Efficiency

Various measures of water-use efficiency are used to compare the relative benefits of different irrigation practices and systems. The most meaningful overall measure of efficiency would compare the output of a system (crop biomass or value of marketable product) to the amount of water allocated as an input into the system. There are many factors to consider (such as type of plants grown, reuse of "wasted" water by others downstream, etc.), so such comparisons must be made with caution.

Application Efficiency. A simpler measure of water-use efficiency, sometimes termed the **water application efficiency**, compares the amount of water available or allocated to irrigate a field to the amount of water actually used in transpiration by the irrigated plants. In this regard, most irrigation systems are quite inefficient, with only about 10–30% of the water that is taken from the source transpired by the desired plants. Table 6.6 gives estimates of the various water losses that typically occur between allocation and transpiration. The table compares average losses in semiarid regions under both rainfed and irrigated agriculture.

Much of the water loss occurs by evaporation and leakage in the reservoirs, canals, and ditches used to store and deliver water to irrigated fields. To reduce these losses during water distribution, ditches can be lined with concrete or plastic (see Figure 6.47). Evaporative losses can be all but eliminated during distribution by the use of pipelines instead of open canals, but this is very much more expensive.

Figure 6.47 *Unlined ditches* (left) *lose much water to adjacent soil areas or to the groundwater. Note the evidence of capillary movement above the water level in the unlined ditch. Concrete-lined irrigation ditches to carry water long distances* (right) *or within a farm* (center) *can increase the efficiency of water delivery to the field. Standard-sized siphon pipes efficiently transfer water from a distribution ditch to the cropped field itself* (center). (Photos courtesy of Ray R. Weil)

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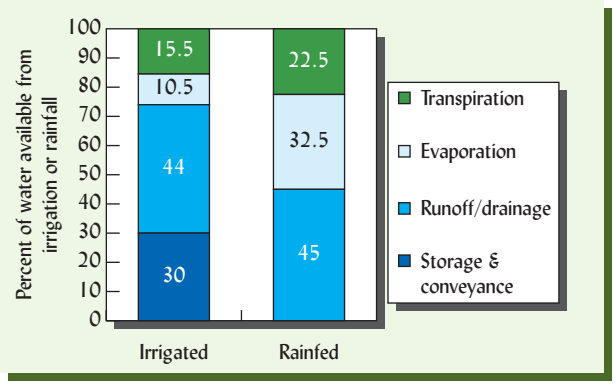

Figure 6.48 *Estimates of average water losses in traditional irrigated and rainfed agriculture in semiarid areas of the world. Available water for irrigated agriculture = water stored in reservoirs or pumped from groundwater, available water for rainfed agriculture = rainfall. Evaporation includes vaporization from both open water and soil surfaces. Some of the water lost by drainage and runoff may be reused by downstream irrigators. Note that an average of 30% of the allocated water is lost in storage or conveyance before it reaches the field.* (Recalculated and graphed from data in Wallace (2000))

Field Water Efficiency. Water-use efficiency *in the field* may be expressed as

$$\text{Field water efficiency, \%} = \frac{\text{Water tranpired by the crop}}{\text{Water applied to the field}} \times 100 \qquad (6.3)$$

Values are usually less than 50%. As shown in Table 6.6, field water efficiency for traditional irrigation systems used in semiarid regions is often as low as 20–25%. For example, if transpiration uses 18% out of the total allocated water of the 70% that reaches the field, the field water efficiency $= 100(18/70) = 25.7\%$. The water delivered to the field that is not transpired by the crop is lost as surface runoff, deep percolation below the root zone, and/or evaporation from the soil surface. Achieving a high level of field water efficiency (or a low level of water wastage) is very dependent on the skill of the irrigation manager and on the methods of irrigation used. As shown in Table 6.6, different irrigation systems vary greatly in their field water efficiencies. We will now turn our attention to a brief description of the principal methods of irrigation in use today.

Surface Irrigation

In these systems water is applied to the upper end of a field and allowed to distribute itself by gravity flow. Usually the land must be leveled and shaped so that the water will flow uniformly across the field. The water may be distributed in **furrows** graded to a slight slope so

Table 6.6
SOME CHARACTERISTICS OF THE THREE PRINCIPAL METHODS OF IRRIGATION

Methods and specific examples	Direct costs of installation,[a] 2013 dollars/ha	Labor requirements	Field water efficiency,[b] %	Suitable soils
Surface: basin, flood, furrow	700–1000	High to low, depending on system	20–50	Nearly level land; not too sandy or rocky
Sprinkler: center pivot, movable pipe, solid set	1000–2000	Medium to low	60–70	Level to moderately sloping; not too clayey
Microirrigation: drip, porous pipe, spitter, bubbler	1200–2500	Low	80–90	Steep to level slopes; any texture, including rocky or gravelly soils

[a]Average ranges from many sources. Costs of required drainage systems not included.
[b]Field water efficiency = 100 × (water transpired by crop/water applied to field).

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that water applied to the upper end of the field will flow down the furrows at a controlled rate (Figure 6.49). In **border irrigation** systems, the land is shaped into broad strips 10–30 m wide, bordered by low dikes.

Water Control. Water is usually brought to surface-irrigated fields in supply ditches or gated pipes (such as are shown in Figures 6.42–6.44). The amount of water that enters the soil is determined by the permeability of the soil and by the length of time a given spot in the field is inundated with water. Achieving a uniform infiltration of exactly the required amount of water is very difficult and depends on controlling the slope and length of the irrigation runs across the field. If the soil is highly permeable (e.g., some loamy sands), too much water may infiltrate near the upper end of the field and too little may reach the lower end (Figure 6.49). On the other hand, for a fine-textured soil, infiltration may be so slow that water flows across the field and ponds up or runs off the lower end without a sufficient amount soaking into the soil. Therefore, in the very sandy soils, leaching loss of water and chemicals is a problem at the upper end of the field. In clayey soils, erosion, runoff, and waterlogging may be problems at the lower end.

The **level basin** technique of surface irrigation, as is used for paddy rice and certain tree crops, alleviates these problems because each basin has no slope and is completely surrounded by dikes that allow water to stand on the area until infiltration is complete. This method is not practical for highly permeable soils into which water would infiltrate so fast that the basin would never fill. On sloping land, terraces can be built in a modification of the level-basin method (Figure 6.50).

Variants of the surface systems have been in use for 5000 years. They require little equipment and are relatively inexpensive to operate. The principal capital cost is usually the initial land shaping, which may be quite expensive if the land is not nearly level to begin with. However, control over leaching and runoff losses is difficult, and the entire soil surface is wetted so that much water is lost by evaporation from the soil and by weed transpiration.

Sprinkler Systems

In sprinkler irrigation, water is sprayed through the air onto a field, simulating rainfall. Thus the entire soil surface, as well as plant foliage (if present), is wetted. This leads to evaporative losses similar to those described for surface systems. Furthermore, an additional 5%–20% of

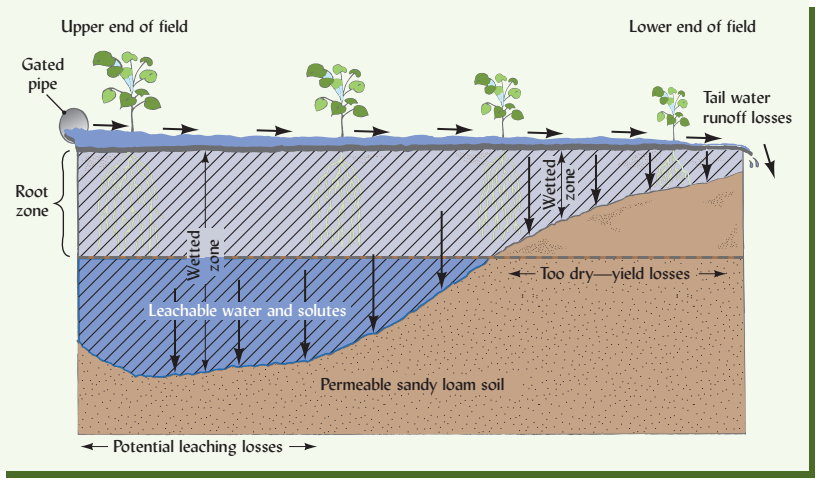

Figure 6.49 *Penetration of water into a coarse-textured soil under surface irrigation. The high infiltration rate causes most of the water to soak in near the gated pipe at the upper end of the field. The uneven penetration of water results in the potential for leaching losses of water and dissolved chemicals at the upper end of the field, while plants at the lower end may receive insufficient water to moisten the entire potential root zone. On a less permeable soil, or on a field with a steep slope, the tail water runoff losses would likely be greater at the lower end and leaching potential less at the upper end.* (Photo and diagram courtesy of Ray R. Weil)

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Figure 6.50 *The level-basin type of surface irrigation.* (Upper left) *Nut trees are flood irrigated on level land in Arizona, USA.* (Lower left) *Level basin irrigation is modified for sloping land in South Asia by construction of terraces on which paddy rice is grown.* (Right) *Whole landscapes can be transformed with level terraces supporting flood irrigation. This type of irrigation is practical only on soils of low permeability.* (Photos courtesy of Ray R. Weil)

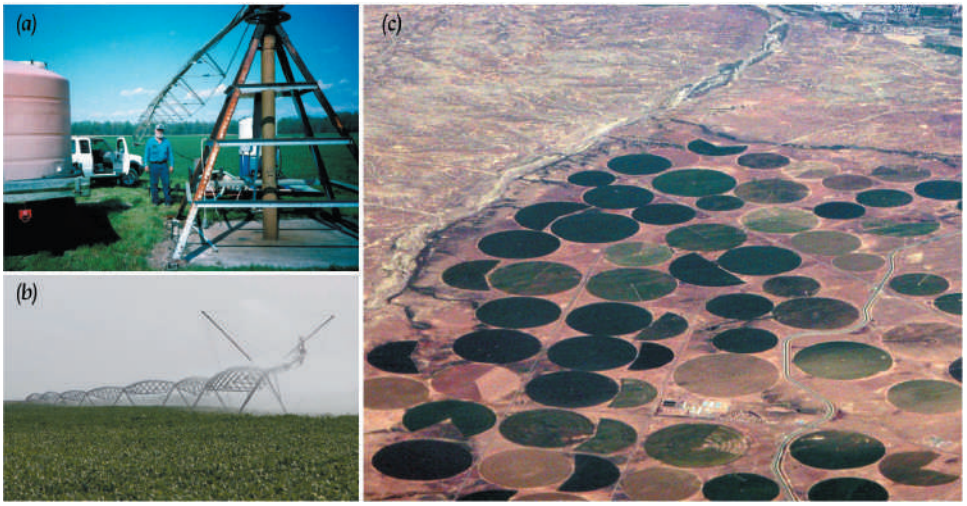

Figure 6.51 *Center pivot irrigation systems.* (a) *A center pivot irrigation system with a heavy duty motor used to pump the water up from the groundwater. Also shown are a large tank of liquid fertilizer and the computer controls that allow nutrients to be injected into the water at precise rates during irrigation events, a process termed fertigation.* (b) *This system is seen from just outside the irrigated circle where the system is making a low-energy, precision application of water to a soybean crop and is rotating slowly toward the left.* (c) *Many such irrigation circles as seen from the air have transformed the hydrology of this arid Texas landscape in the United States.* (Photos courtesy of Ray R. Weil)

the applied water may be lost by evaporation or windblown mist as the drops fly through the air. One advantage is that plants often respond positively to the cooler, better-aerated sprinkler water. A disadvantage is that wet leaves may increase the incidence of fungal diseases in some plants, such as grapes, fruit trees, and roses, so sprinkler systems are not often used for these plants.

Water Control. A sprinkler system should be designed to deliver water at a rate that is less than the infiltration capacity of the soil, so that runoff or excessive percolation will not occur. In practice, runoff and erosion may be problems if the soil infiltration capacity is low, the land is relatively steep, or too much water is applied in one place. Water is sometimes lost by deep percolation because more water falls near the sprinkler than farther from it. Overlapping of spray circles can help achieve a more even distribution of water. Because of better control over application rates, the field water-use efficiency is generally higher for sprinkler systems than for surface systems, especially on coarse-textured soils.

Suitable Soils. Sprinkler irrigation is practical on a wider range of soil conditions than is the case for the surface systems. Various types of sprinkler systems are adapted to moderately sloping as well as level land (Figure 6.51*c*). They can be used on soils with a wide range of textures, even those too sandy for surface irrigation systems. Advanced center pivot systems use computer-controlled nozzles to vary the amount of water applied according to the soil properties encountered as the rig rotates around a field (Figure 6.52). For instance rocky or

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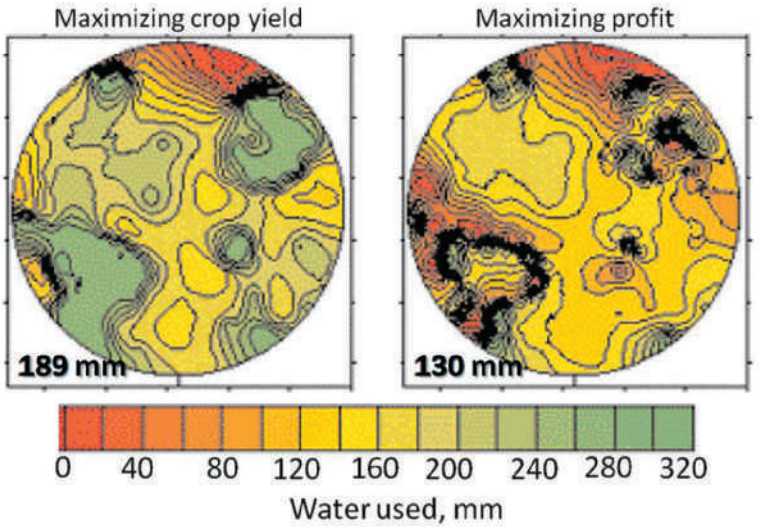

Figure 6.52 *Modern sprinkler irrigation offers the potential for precision water application. With variable application controls on each sprinkler nozzle, advanced center pivot systems are capable of applying water in amounts determined by the particular soil properties at each location in a circular field. The two maps show how much water (mm of irrigation) should have been applied to this 7 hectare sandy coastal plain field to maximize crop yield* (left) *or profitability* (right). *The optimized amount of irrigation was calculated from quadratic models taking into account the mapped soil properties (such as water holding capacity) and actual crop responses to varying amounts of irrigation water applied to nearly 400 small plots located throughout the field.* [Modified from Sadler (2005)]

very sandy spots with low potential for crop growth and low water holding capacity may receive little or no water while areas of better soils with high production potential may receive larger amounts of water. In addition, soil water sensors (such as the capacitance sensor shown in Figure 5.16) can be embedded in the soil at various location s around a field and wirelessly connected to a computer system that can then control the amount of water applied to maintain optimal soil water content at each location.

Equipment. The equipment costs for sprinkler systems are higher than those for surface-flow systems. Large pressure pumps and specialized pipes and nozzles are required. Some types of sprinkler systems are set in place, others are moved by hand, and still others are self-propelled, either moving in large circles around a central pivot or rolling slowly across a rectangular field. Most systems can be automated and adapted to deliver doses of pesticides or soluble fertilizers to plants (Figure 6.52*a*).

Microirrigation

The most efficient irrigation systems in use today are those using microirrigation, whereby only a small portion of the soil is wetted (Figure 6.53*a*,*c*) in contrast to the complete wetting accomplished by most surface and sprinkler systems. The "micro" in microirrigation may also refer to the tiny amounts of water applied at any one time and the miniature size of the equipment involved.

Perhaps the best-established microirrigation system is *drip* (or *trickle*) *irrigation*, in which tiny emitters attached to plastic tubing apply water to the soil surface alongside individual plants. In some cases the tubing and emitters are buried 20–50 cm deep so the water soaks directly into the root zone. In either case, water is applied at a low rate (sometimes drop by drop) but at a high frequency, with the objective of maintaining optimal soil water availability in the immediate root zone while leaving most of the soil volume dry (Figure 6.53). Table 6.7 illustrates the high field-water efficiency of drip irrigation.

Other forms of microirrigation that are especially well adapted for irrigating individual trees include *spitters* (microsprayers) and *bubblers* (small vertical standpipes). The bubblers (and usually the spitters) require that a small level basin be formed in the soil under each tree.

Water Control. Water is normally carried to the field in pipes, run through special filters (Figure 6.53*d*) to remove any grit or chemicals that might clog the tiny holes in the emitters (filtering is not necessary for bubblers), and then distributed throughout the field by means of a network of plastic tubes. Soluble fertilizers may be added to the water as needed.

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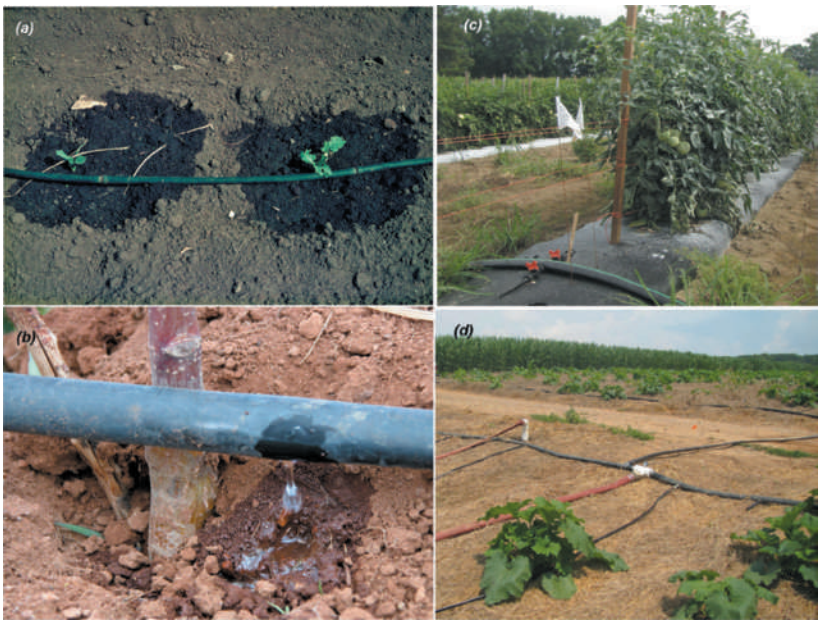

Figure 6.53 *Four examples of microirrigation that ensure the root zone is kept almost continuously at optimal moisture content by application of small quantities of water at high frequency (such as once or twice a day).* (a) Drip *or* trickle *irrigation with a single emitter for each seedling in a cabbage field in Malawi.* (b) *Irrigation applied drop by drop to an individual tree in a young apple orchard in Mexico.* (c) *Microirrigation is often used in conjunction with plastic mulch to control the loss of water by evaporation and weed transpiration. In this tomato field, a main water supply line runs perpendicular to the crop rows, while smaller drip lines run from the supply line under the plastic with emitters near each plant.* (d) *Microirrigation lines in a no-till pumpkin field mulched by thick cover crop residues. The white object is an in-line filter that removes sediment particles before they can clog the fine emitter holes. In each case, irrigation wets only the small portion of the soil in the immediate root zone of individual plants, thus limiting the amount of water required and reducing weed growth and evaporation in the non-moistened area.* (Photos courtesy of Ray R. Weil)

If properly maintained and managed, microirrigation allows much more control over water application rates and spatial distribution than do either surface or more sprinkler systems. Losses by supply-ditch seepage, sprinkler-drop evaporation, runoff, drainage (in excess of that needed to remove salts), soil evaporation, and weed transpiration can be greatly reduced or eliminated. Once in place, the labor required for operation is modest and the system can be largely automated.

Microirrigation often produces healthier plants and higher crop yields because the plant is never stressed by low water potentials or low aeration conditions that are associated with the feast-or-famine regime of infrequent, heavy water applications made by all surface irrigation systems and most sprinkler systems. A disadvantage or risk is that there is very little water stored in the soil at any time, so even a brief breakdown of the system could be disastrous in hot, dry weather.

Equipment. The capital costs per hectare for microirrigation tend to be higher than for other systems (see Table 6.6), but the differences are not so great if the cost of drainage systems for control of salinity and waterlogging in surface systems, the costs of high-pressure pumping in sprinkler systems, and the real value of wasted water are taken into account. Because of its high water-use efficiency, microirrigation is most profitable where water supplies are scarce and expensive and where high-valued plants such as fruit trees or vegetables are being grown.

6.10 CONCLUSION

The hydrologic cycle encompasses all movements of water on or near the Earth's surface. It is driven by solar energy, which evaporates water from the ocean, the soil, and vegetation. The water cycles into the atmosphere, returning elsewhere to the soil and the oceans in rain and snow.

The soil is an essential component of the hydrologic cycle. It receives precipitation from the atmosphere, rejecting some of it, which is then forced to run off into streams and rivers, and absorbing the remainder, which then moves downward to be either transmitted to the groundwater, taken up and later transpired by plants, or evaporated directly from soil surfaces and returned to the atmosphere.

Water moves within the soil as a liquid by the processes of gravitational drainage, capillary action and redistribution by plant roots. The behavior of water is governed by the same

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Table 6.7
EFFICIENCIES OF SELECTED IRRIGATION METHODS IN THE HIGH PLAINS OF TEXAS
Note that improved irrigation methods show 20%–35% higher efficiency and considerably lower water requirements. Additional improvements in water use efficiency related to plant availability of the water added are not considered here.

Irrigation method	Typical efficiency, %	Water application needed to add 100 mm to root zone, mm	Water savings over conventional furrow, %
Conventional furrow	60	167	—
Furrow with surge valve	80	125	25
Low-pressure sprinkler	80	125	25
LEPA sprinkler[a]	90–95	105	37
Drip	95	105	37

[a]LEPA refers to low-energy precision application that delivers the water close to the plants.
Data selected from Postel (1999) based on data from the High Plains Underground Water Conservation District (Lubbock, Texas).

set of principles in both soils and plants: water moves in response to differences in energy levels, moving from higher to lower water potential. These principles can be used to manage water more effectively and to increase the efficiency of its use.

Management practices should encourage movement of water into well-drained soils while minimizing evaporative losses from the soil surface. These two objectives will provide as much water as possible for plant uptake and groundwater recharge. "Green water" as water from the soil is called, must satisfy the T requirements of healthy leaf surfaces; otherwise, plant growth will be limited by water stress. Practices that leave plant residues on the soil surface and that maximize plant shading of this surface will help achieve high efficiency of water use by minimizing evaporation losses.

Extreme soil wetness, characterized by surface ponding and saturated conditions, is a natural and necessary condition for wetland ecosystems. However, extreme wetness is detrimental for most other land uses. Drainage systems have therefore been developed to hasten the removal of excess water from soil and lower the water table so that upland plants can grow without aeration stress, and so the soil can better bear the weight of vehicular and foot traffic.

A septic tank drain field operates as a drainage system in reverse. Septic wastewaters can be disposed of and treated by soils if the soils are freely draining. Soils with low permeability or high water tables may indicate good conditions for wetland creation or appropriate sites for installation of artificial drainage for agricultural use, but they are not generally suited for septic tank drain fields.

"Blue water," the term for water withdrawn from streams or wells, can be applied to the soil as irrigation, greatly enhancing plant growth, especially in regions with scarce precipitation. With increasing competition for limited global and local water resources, it is essential that irrigators manage water with maximal efficiency so that the greatest production can be achieved with the least waste of water resources. Such efficiency is encouraged by practices that favor transpiration over evaporation, such as mulching and the use of microirrigation.

The operation of the hydrologic cycle causes changes in soil water content, which in turn influence other soil properties, most notably soil aeration and temperature. These soil properties will be the subjects of the next chapter.

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STUDY QUESTIONS

1. You know that the forest vegetation that covers a 120 km^2 wildland watershed uses an average of 4 mm of water per day during the summer. You also know that the soil averages 150 cm in depth and at field capacity can store 0.2 mm of water per mm of soil depth. However, at the beginning of the season the soil was quite dry, holding an average of only 0.1 mm/mm. As the watershed manager, you are asked to predict how much water will be carried by the streams draining the watershed during the 90-day summer period when 450 mm of precipitation falls on the area. Use the water balance equation to make a rough prediction of the stream discharge as a percentage of the precipitation and in cubic meters of water.
2. Draw a simple diagram of the hydrologic cycle using a separate arrow to represent these processes: *evaporation*, *transpiration*, *infiltration*, *interception*, *percolation*, *surface runoff*, and *soil storage*.
3. Describe and give an example of the *indirect* effects of plants on the hydrologic balance through their effects on the soil.
4. State the basic principle that governs how water moves through the SPAC. Give two examples, one at the soil–root interface and one at the leaf–atmosphere interface.
5. Define *potential evapotranspiration* and explain its significance to water management.
6. What is the role of evaporation (E) from the soil in determining water-use efficiency, and how does it affect ET? List three practices that can be used to control losses by E.
7. Weed control should reduce water losses by what process?
8. Hydraulic lift is a special case of hydraulic redistribution. Describe this phenomenon and the conditions that favor its operation.
9. Comment on the relative advantages and disadvantages of organic versus plastic mulches.
10. What does conservation tillage conserve? How does it do it?
11. The small irrigation project you manage collects 2,000,000 m^3 of water annually in a reservoir. Of this, 20% evaporates from the reservoir surface during the year. Of the remaining water, 25% is lost by evaporation and percolation into the soil during distribution via unlined canals before the water reaches the fields. The water is then applied by furrow irrigation, with averages 20% of the water applied percolating below the crop root zone, 20% running off into collection canals at the low end of the field, and 30% evaporating from the soil surface. By the time of crop harvest, ET has dried the soil to about the same water content it had before irrigation began. Average ET is 7 mm/day for a 180-day irrigation season and crop water-use efficiency averages 1.1 kg of dry matter/m^3 water transpired. Show calculations to estimate:
    (a) the overall water-use efficiency of the project (kg output/m^3 water allocated),
    (b) the application water efficiency for the project,
    (c) the field water efficiency for the project,
    (d) the number of hectares that can be irrigated in this project.
12. Explain under what circumstances earthworm channels might increase downward saturated water flow, but not have much effect on the leaching of soluble chemicals applied to the soil.
13. What will be the effect of placing a perforated drainage pipe in the capillary fringe zone just above the water table in a wet soil? Explain in terms of water potentials.
14. What soil features may limit the use of a site for a septic tank drain field?
15. Which irrigation systems are likely to be used where: (a) water is expensive and the market value of crops produced per hectare is high, and (b) the cost of irrigation water is subsidized and the value of crop products that can be produced per hectare is low? Explain.

REFERENCES

Bäse, F., H. Elsenbeer, C. Neill, and A. V. Krusche. 2012. "Differences in throughfall and net precipitation between soybean and transitional tropical forest in the southern Amazon, Brazil." *Agriculture, Ecosystems & Environment* **159**:19–28.

Basso, B., and J. T. Ritchie. 2012. "Assessing the impact of management strategies on water use efficiency using soil–plant–atmosphere models." *Vadose Zone Journal* **11**:doi:10.2136/vzj2011.0173.

Brooks, J.R. 2015. "Water, bound and mobile." *Science* **349**:138–139.

Chen, G., and R. R. Weil. 2011. "Root growth and yield of maize as affected by soil compaction and cover crops." *Soil and Tillage Research* **117**:17–27.

Day, R. L. et al. 1998. "Water balance and flow patterns in a fragipan using in situ soil block." *Soil Science* **163**:517–528.

Evans, T. A., T. Z. Dawes, P. R. Ward, and N. Lo. 2011. "Ants and termites increase crop yield in a dry climate." *Nature Communication* **2**:262.

Farahani, H. J. et al. 1998. "Soil water storage in dryland cropping systems: The significance of cropping intensification." *Soil Science Society of America Journal* **62**:984–991.

Gburek, W. J., B. A. Needelman, and M. S. Srinivasan. 2006. "Fragipan controls on runoff generation: Hydropedological implications at landscape and watershed scales." *Geoderma* **131**:330–344.

FOR REFERENCE PURPOSES ONLY

Golman, E. 2008. "Greening gray streets - can it clean the waters below?" http://www.mdsg.umd.edu/CQ/v07n2/side1/index.html.

Greb, B. W. 1983. "Water conservation: Central Great Plains." In H. E. Dregue and W. O. Willis (eds.). *Dryland Agriculture*. Agronomy Series No. 23. American Society of Agronomy, Madison, WI.

Haynes, J. L. 1954. "Ground rainfall under vegetative canopy of crops." *Journal of American Society of Agronomy* **46**:67–94.

Hillel, D. 1995. *The Rivers of Eden*. Oxford University Press, New York.

Hillel, D. 1997. *Small-Scale Irrigation for Arid Zones*. FAO Development Series 2. U.N. Food and Agriculture Organization, Rome.

Howell, T. A. 2001. "Enhancing water use efficiency in irrigated agriculture." *Agronomy Journal* **93**:281–289.

Jeswani, H. K., and A. Azapagic. 2011. "Water footprint: Methodologies and a case study for assessing the impacts of water use." *Journal of Cleaner Production* **19**:1288–1299.

Jury, W. A., and H. Fluhler. 1992. "Transport of chemicals through soil: Mechanisms, models, and field applications." *Advances in Agronomy* **47**:141–201.

Kemper, W. D., C. E. Bongert, and D. M. Marohn. 2012. "Corn response to tillage and water table depth." *Journal of Soil and Water Conservation* **67**:31A–36A.

Kittridge, J. 1948. *Forest Influences: The Effects of Woody Vegetation on Climate, Water and Soil*. McGraw-Hill, New York.

Lal, R. 2015. "World water resources and achieving water security". *Agronomy Journal* **107**:1526–1532.

Lascano, R. J., and R. E. Sojka (eds.). 2007. *Irrigation of Agricultural Crops*. Agronomy Monograph 30. American Society of Agronomy, Madsion, WI, pp. 1–664.

Linde, D. T., T. L. Watschke, and J. A. Borger. 1995. "Surface runoff assessment from creeping bent grass and perennial ryegrass turf." *Agronomy Journal* **87**:176–182.

Mazza, G., E. Amorini, A. Cutini, and M. Manetti. 2011. "The influence of thinning on rainfall interception by *Pinus pinea* L. in Mediterranean coastal stands (Castel Fusano—Rome)." *Annals of Forest Science* **68**:1323–1332.

Molden, D., T. Oweis, P. Steduto, P. Bindraban, M. A. Hanjra, and J. Kijne. 2010. "Improving agricultural water productivity: Between optimism and caution." *Agricultural Water Management* **97**:528–535.

Nagy, R. C., B. G. Lockaby, B. Helms, L. Kalin, and D. Stoeckel. 2011. "Water resources and land use and cover in a humid region: The southeastern United States." *Journal of Environmental Quality* **40**:867–878.

Oki, T. 2011. "Global hydrology." In W. Peter (ed.). *Treatise on Water Science*, Vol. 2. Elsevier, Oxford, pp. 3–25.

Pfister, S., P. Bayer, A. Koehler, and S. Hellweg. 2011. "Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use." *Environmental Science & Technology* **45**:5761–5768.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* Worldwatch Institute, Washington, DC.

Prieto, I., C. Armas, and F. I. Pugnaire. 2012. "Water release through plant roots: New insights into its consequences at the plant and ecosystem level." *New Phytologist* **193**:830–841.

Rosegrant, M. W., X. Cai, and S. A. Cline. 2002. "Global water outlook to 2025: Averting in impending crisis." International Food Policy Research Institute and the International Water Management Institute, Washington, DC. http://www.ifpri.org/pubs/fpr/fprwater2025.pdf.

Sadler, E. J., R. G. Evans, K. C. Stone, and C. R. Camp. 2005. "Opportunities for conservation with precision irrigation." *Journal of Soil and Water Conservation* **60**:371–378.

Sekiya, N., H. Araki, and K. Yano. 2011. "Applying hydraulic lift in an agroecosystem: Forage plants with shoots removed supply water to neighboring vegetable crops." *Plant and Soil* **341**:39–50.

Skaggs, R. W., and J. van Schilfgaarde (eds.). 1999. *Agricultural Drainage*. Agronomy Series No. 38. American Society of Agronomy, Crop Science Society of. America, Soil Science Society of America, Madison, WI.

Skaggs, R. W., N. R. Fausey, and R. O. Evans. 2012. "Drainage water management." *Journal of Soil and Water Conservation* **67**:167A–172A.

Soil Survey Staff. 1993. *National Soil Survey Handbook*. Title 430-VI. USDA Natural Resources Conservation Service, Washington, DC.

Starrett, S. K., N. E. Christians, and T. Al Austin. 1996. "Movement of pesticides under two irrigation regimes applied to turfgrass." *Journal of Environmental Quality* **25**:566–571.

Steidle Neto, A. J., A. Ribeiro, D. d. C. Lopes, O. Sacramento Neto, d. vio Bahia, W. G. Souza, alves, and M. O. Santana. 2012. "Simulation of rainfall interception of canopy and litter in eucalyptus plantation in tropical climate." *Forest Science* **58**:54–60.

Swank, W. T., J. M. Vose, and K. J. Elliot. 2001. "Long-term hydrologic and water quality responses following commercial clear cutting of mixed hardwoods on a southern Appalachian catchment." *Forest Ecology & Management* **143**:163–178.

Tyree, M. T. 2003. "The ascent of water." *Nature* **423**:923.

Unger, P. W., and R. L. Baumhardt. 1999. "Factors related to dryland grain sorghum yield increases: 1939 through 1997." *Agronomy Journal* **91**:870–875.

Waddell, J., and R. Weil. 1996. "Water distribution in soil under ridge-till and no-till corn." *Soil Science Society of America Journal* **60**:230–237.

Wallace, J. S. 2000. "Increasing agricultural water use efficiency to meet future food production." *Agriculture, Ecosystems and Environment* **82**:105–119.

Zanders, J. 2001. "Urban development and soils." Soil Horizons—A Newsletter of Landcare Research New Zealand, Ltd. 6 (Nov.):6.

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7 Soil Aeration and Temperature

A grassland wildfire heats and blackens soil (Ray R. Weil)

The naked earth is warm with Spring.
—*Julian Grenfell*, Into Battle

It is a central maxim of ecology that "everything is connected to everything else." This interconnectedness is one reason why soils are such fascinating (and challenging) objects of study. In this chapter we shall explore two aspects of the soil environment, aeration and temperature; they are not only closely connected to each other but are both also intimately influenced by many of the soil properties discussed in other chapters.

Since air and water share the pore space of soils, it is not surprising that much of what we learned about the texture, structure, and porosity of soils (Chapter 4) and the retention and movement of water in soils (Chapters 5 and 6) will have direct bearing on soil aeration. In addition, chemical and biological processes also affect, and are affected by, soil aeration.

For the growth of plants and the activity of microorganisms, soil aeration status can be just as important as soil moisture status and can sometimes be even more difficult to manage. In most forest, range, agricultural, and ornamental applications, a major management objective is to maintain a high level of oxygen in the soil for root respiration. Yet it is also vital that we understand the chemical and biological changes that take place when the oxygen supply in the soil is depleted.

Soil temperatures affect plant and microorganism growth and also influence soil drying by evaporation. The movement and retention of heat energy in soils are often ignored, but they hold the key to understanding many important soil phenomena, from frost-damaged pipelines and pavements to the spring awakening of biological activity in soils. The unusually high soil temperatures that result from fires on forest-, range-, or croplands can markedly change critical physical, chemical, and biological aspects of the soil system.

We will see that warm soil temperatures influence soil aeration largely through their stimulating effects on the growth of plants and soil organisms and on the rates of biochemical reactions. Nowhere are these interrelationships more critical than in the water-saturated soils, oxygen-depleted of wetlands, ecosystems that will therefore receive special attention in this chapter.

7.1 SOIL AERATION—THE PROCESS

In order for plant roots and other soil organisms to readily carry on respiration, the soil must be well ventilated. Good ventilation allows the exchange of gases between the soil and the atmosphere to supply enough oxygen (O_2) while preventing the potentially toxic accumulation of gases such as carbon dioxide (CO_2), methane (CH_4), and ethylene (C_2H_6). Soil aeration status involves the rate of such ventilation, as well as the proportion of pore

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spaces filled with air, the composition of that soil air, and the resulting chemical oxidation or reduction potential in the soil environment.

Soil Aeration in the Field

Oxygen availability in field soils is regulated by three principal factors: (1) *soil macroporosity* (as affected by texture and structure), (2) *soil water content* (as it affects the proportion of porosity that is filled with air), and (3) *O_2 consumption* by respiring organisms (including plant roots and microorganisms). The term *poor soil aeration* refers to a condition in which the availability of O_2 in the root zone is insufficient to support optimal growth of upland plants and aerobic microorganisms. Typically, poor aeration becomes a serious impediment to plant growth when O_2 concentration drops below 0.1 L/L. This often occurs when more than 80–90% of the soil pore space is filled with water. The high soil water content not only leaves less than 10–20% of the pore space for air storage, but, more important, the water blocks the pathways by which gases could exchange with the atmosphere. Compaction can also cut off gas exchange by decreasing pore size and total pore space, even if the soil is not very wet and has a relatively large percentage of air-filled pores.

Excess Moisture

When all (or nearly all) of the soil pores are filled with water, the soil is said to be ***water saturated*** or ***waterlogged***. Waterlogged soil conditions are typical of wetlands and may also occur for short periods of time on upland sites. In well-drained soils, saturated conditions may occur temporarily during a heavy rainstorm, when excess irrigation water is applied, or if wet soil has been compacted by plowing or by heavy machinery. Plants adapted to life in waterlogged soils are termed ***hydrophytes***. Examples are sedges and certain grass species, including rice, that transport oxygen for respiration down to their roots via hollow structures in their stems and roots known as ***aerenchyma*** tissues (Figure 7.1, *left*). Mangroves (Figure 7.1, *right*) and other hydrophytic trees produce aerial roots and other structures that allow their roots to obtain O_2 while growing in water-saturated soils.

Most plants, however, are dependent on a supply of oxygen from the soil to their roots and suffer dramatically if good soil aeration is not maintained by drainage or other means (Figure 7.2). Some plants succumb to O_2 deficiency or toxicity of other gases within hours after the soil becomes saturated. Other upland plants are capable of sensing low O_2 levels and adapting their physiology or morphology (for instance, by developing aerenchyma or slowing their oxygen use) within a few days or weeks to alleviate the aeration stress.

Gaseous Interchange

The more rapidly roots and microbes use up oxygen and release carbon dioxide, the greater is the need for ventilation—the exchange of gases between the soil and the atmosphere. This exchange is facilitated by two mechanisms, ***mass flow*** and ***diffusion***. Mass flow of air is

Figure 7.1 *Certain plants, termed hydrophytes, are able to grow in saturated soils that are virtually devoid of oxygen.* (Left) *Many herbaceous hydrophytes have aerenchyma tissue that provides hollow passageways for oxygen to move down into their roots.* (Right) *Mangrove trees are woody hydrophytes that have developed root projections termed pneumatophores-aerial roots that enable them to access oxygen directly from the atmosphere. Mangroves have also evolved means of excluding the salts in the ocean water.* (Photos courtesy of Ray R. Weil)

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Figure 7.2 *Most plants depend on the soil to supply oxygen for root respiration and therefore are disastrously affected by even relatively brief periods of soil saturation during which oxygen becomes depleted.* (Left) *Sugar beets on a clay loam soil dying where the soil has become water-saturated in a compacted area.* (Right) *Pine trees dying in a sandy soil area that has become saturated as a result of flooding by beavers.* (Photos courtesy of Ray R. Weil)

enhanced by fluctuations in soil moisture content that force air in or out of the soil and by wind and changes in barometric pressure. However, the great bulk of gaseous interchange in soils occurs by *diffusion*.

Through diffusion, each gas moves in a direction determined by its own partial pressure. The *partial pressure* of a gas in a mixture is simply the pressure this gas would exert if it alone were present in the volume occupied by the mixture. Thus, if the pressure of air is 100 kPa (~1 atmosphere), the partial pressure of oxygen, which makes up about 21% (0.21 L/L) of the air by volume, is approximately 21 kPa.

Diffusion allows extensive gas movement from one area to another even though there is no overall pressure gradient for the total mixture of gases. There is, however, a concentration gradient for each individual gas, which may be expressed as a *partial pressure gradient*. As a consequence, the higher concentration of oxygen in the atmosphere will result in a net movement of this particular gas into the soil. Carbon dioxide and water vapor normally move in opposite directions, since the partial pressures of these two gases are generally higher in the soil air than in the atmosphere. A representation of the principles involved in diffusion is given in Figure 7.3.

7.2 MEANS OF CHARACTERIZING SOIL AERATION

The aeration status of a soil can be characterized in several ways, including: (1) the content of oxygen and other gases in the soil atmosphere, (2) the air-filled soil porosity, and (3) the chemical oxidation–reduction (redox) potential.

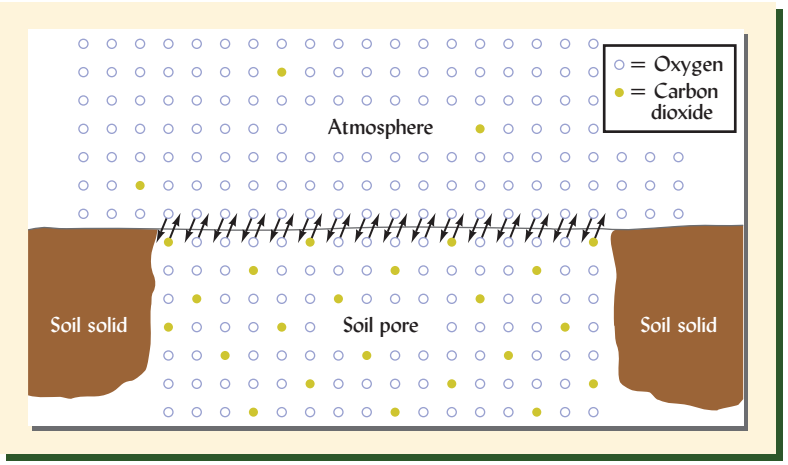

Figure 7.3 *Gases move by diffusion between the atmosphere and soil pores. The total gas pressure is the same on both sides of the boundary. However, the partial pressure of oxygen (O_2) is greater in the atmosphere and that of carbon dioxide (CO_2) is greater in the soil pores. Therefore, O_2 molecules diffuse into the soil pore where their number per unit volume is lower. The CO_2 molecules move in the opposite direction owing to the higher partial pressure of this gas in the soil pore. Diffusion of O_2 into the soil pores and CO_2 into the atmosphere will continue as long as respiration by roots and microorganisms in the soil consumes O_2 and releases CO_2.*

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Gaseous Composition of the Soil Air

Oxygen. The atmosphere above the soil contains nearly 21% O_2, 0.035% CO_2, and more than 78% N_2. In comparison, soil air has about the same level of N_2 but is consistently lower in O_2 and higher in CO_2. The O_2 content may be only slightly below 20% in the upper layers of a soil with an abundance of macropores. It may drop to less than 5% or even to near zero in the lower horizons of a poorly drained soil with few macropores. Once the supply of O_2 is exhausted, the soil environment is said to be **anaerobic**.

Low O_2 contents are typical of wet soils. Even in well-drained soils, marked reductions in the O_2 content of soil air may follow a heavy rain, especially if oxygen is being rapidly consumed by actively growing plant roots or by microbes decomposing readily available supplies of organic materials (Figure 7.4). Oxygen depletion in this manner occurs most rapidly when the soil is warm.

Carbon Dioxide. Since the N_2 content of soil air is relatively constant, there is a general inverse relationship between the contents of the other two major components of soil air—O_2 and CO_2—with O_2 decreasing as CO_2 increases. Although the actual differences in CO_2 amounts may not be impressive, they are significant, comparatively speaking. Thus, when the soil air contains only 0.35% CO_2, this gas is about ten times as concentrated as it is in the atmosphere. In cases where the CO_2 content becomes as high as 10%, it may be toxic to some plant processes.

Other Gases. Soil air usually is much higher in water vapor than is the atmosphere, being essentially saturated except at or very near the surface of the soil (see Section 5.7). Also, under waterlogged conditions, the concentrations of gases such as methane (CH_4) and hydrogen sulfide (H_2S), which are formed as organic matter decomposes, are notably higher in soil air. Another gas produced by anaerobic microbial metabolism is ethylene (C_2H_4). This is very bioactive and is involved in how some plants sense the depletion of O_2 in their root zones. When gas exchange rates between the atmosphere and the soil are so slow that ethylene that

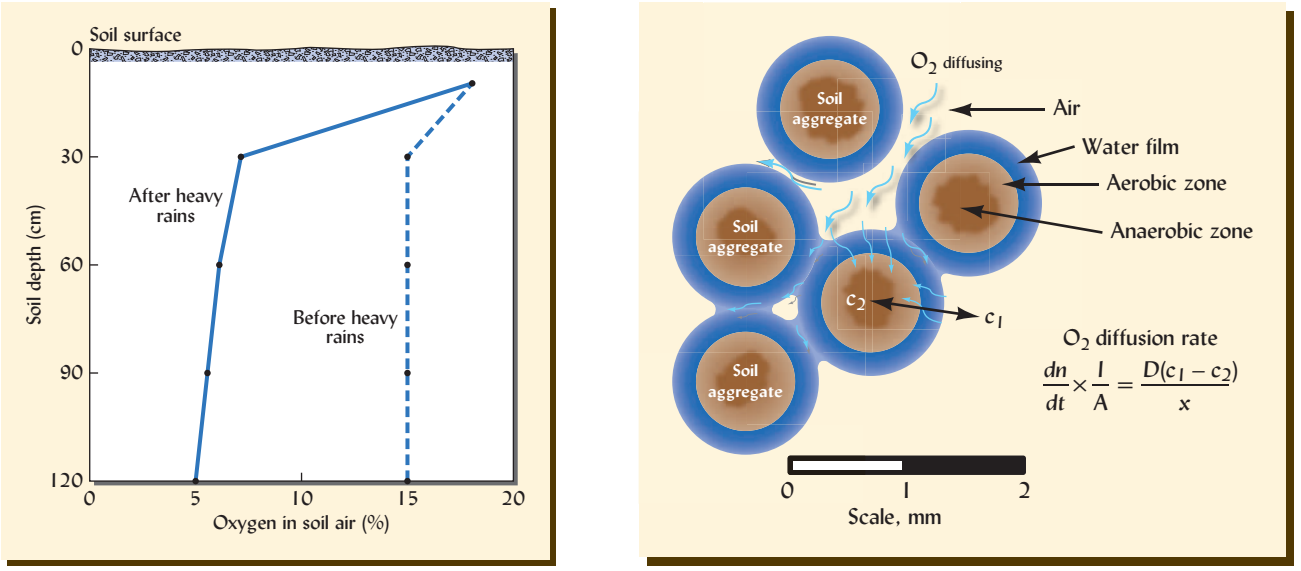

Figure 7.4 (Left) *Oxygen content of soil air before and after heavy rains in a soil on which cotton was being grown. The rainwater replaced most of the soil air, pushing it out of soil pores. e Respiration by roots and soil organisms consumed much of the oxygen remaining. The carbon dioxide content (not reported) probably showed a corresponding increase.* (Right) *Oxygen diffusion through the soil (squiggly arrows) is inhibited by water filled pores because the diffusion coefficient* (D) *for O_2 is about 10,000 times smaller through water than through air. In a moist soil the micropores inside aggregates are mostly filled with water, making it difficult for O_2 to reach the center of such aggregates.* [*Left*, redrawn from Patrick (1977); used with permission of the Soil Science Society of America, *Right*, courtesy of Ray R. Weil]

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accumulates, even in concentrations as low as 1 μL/L (0.0001%), root growth of a number of plants has been shown to be inhibited.

Air-Filled Porosity

In Chapter 1 (Figure 1.21) we noted that the ideal soil composition for plant growth would include close to a 50:50 mix of air and water in the soil pore space, or about 25% air in the soil, by volume (assuming a total porosity of 50%) (Figure 1.21). Many researchers believe that microbiological activity and plant growth become severely inhibited in most soils when air-filled porosity falls below 20% of the pore space or 10% of the total soil volume (with correspondingly high water contents).

One of the principal reasons that high water contents cause oxygen deficiencies for roots is that water-filled pores block the diffusion of oxygen into the soil to replace that used by respiration (Figure 7.4, *right*). In fact, oxygen diffuses 10,000 times faster through a pore filled with air than through a similar pore filled with water.

7.3 OXIDATION–REDUCTION (REDOX) POTENTIAL[1]

Important chemical characteristics related to soil aeration are the reduction and oxidation states of the chemical elements.

Redox Reactions

The reaction that takes place when the reduced state of an element is changed to the oxidized state may be illustrated by the oxidation of two-valent iron [Fe^{2+} or Fe(II)] in FeO to the trivalent form [Fe^{3+} or Fe(III)] in FeOOH

$$\underset{\text{Fe(II)}}{\overset{(2+)}{2FeO}} + 2H_2O \rightleftharpoons \underset{\text{Fe(III)}}{\overset{(3+)}{2FeOOH}} + 2H^+ + 2e^- \qquad (7.1)$$

As reaction (7.1) proceeds to the *right*, each Fe(II) loses an electron (e^-) to become Fe(III) and forms H^+ ions by hydrolyzing H_2O. These H^+ ions lower the pH. When the reaction proceeds to the *left*, FeOOH acts as an **electron acceptor** and the pH rises as H^+ ions are consumed. The tendency or potential for electrons to be transferred from one substance to another in such reactions is termed the **redox potential** (E_h), which can be measured using a platinum electrode attached to a millivolt meter.

The redox potential is usually expressed in volts or millivolts. As is the case for water potential (Section 5.3), redox potential is related to a reference state, in this case the hydrogen couple $\frac{1}{2}H_2 \leftrightarrow 2H^+ + e^-$ whose redox potential is arbitrarily taken as zero. If a substance will accept electrons easily, it is known as an *oxidizing agent;* if a substance supplies electrons easily, it is a *reducing agent*.

Role of Oxygen Gas

Oxygen gas (O_2) is an important example of a strong oxidizing agent, since it rapidly accepts electrons from many other elements. All aerobic respiration requires O_2 to accept the electrons released as living organisms oxidize organic carbon to provide energy for life.

Oxygen can oxidize both organic and inorganic substances. Keep in mind, however, that as it oxidizes another substance, O_2 is in turn reduced. This reduction process can be seen in the following reaction:

$$\overset{(0)}{\tfrac{1}{2}O_2} + 2H^+ + 2e^- \rightleftharpoons \overset{(2-)}{H_2O} \qquad (7.2)$$

[1]For reviews of redox reactions in soils, see Bartlett and James (1993) and Bartlett and Ross (2005).

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Note that the oxygen atom which has zero charge in elemental O_2 accepts two electrons, taking on a charge of −2 when it becomes part of the water molecule. These electrons could have been donated by two molecules of FeO undergoing oxidation, as shown in reaction (7.1). If we combine equations (7.1) and (7.2), we can see the overall effect of oxidation and reduction

$$\begin{array}{rcl} 2FeO + 2H_2O & \rightleftharpoons & 2FeOOH + 2H^+ + 2e^- \\ \frac{1}{2}O_2 + 2H^+ + 2e^- & \rightleftharpoons & H_2O \\ \hline 2FeO + \frac{1}{2}O_2 + H_2O & \rightleftharpoons & 2FeOOH \end{array} \qquad (7.3)$$

The donation and acceptance of electrons (e^-) and H^+ ions on each side of the equations have balanced each other and therefore do not appear in the combined reaction. However, for the specific reduction and oxidation reactions, they are both very important.

In a well-aerated soil with plenty of gaseous O_2, the E_h is in the range of 0.4–0.7 volt (V). As aeration is reduced and gaseous O_2 is depleted, the E_h declines to about 0.3–0.35 V. If organic matter–rich soils are flooded under warm conditions, E_h values as low as −0.3 V can be found.

The relationship between changes in O_2 content and E_h of a wet soil is shown in Figure 7.5. Within a day or two after a warm soil becomes water saturated, aerobic and facultative microorganisms oxidizing organic carbon in the soil (see Section 11.2) respire most of the O_2 initially present, thereby lowering the E_h of the soil solution.

Other Electron Acceptors

As O_2 becomes depleted and E_h drops, reducing conditions become established. With no O_2 available, only **anaerobic** microorganisms can survive. They must use substances other than O_2 as the terminal electron acceptors for their metabolism. For example, they may use iron in soil minerals. As they reduce iron, the E_h drops still further because electrons are consumed. The pH simultaneously rises because the reaction consumes H^+ ions:

$$\underset{\text{Fe(III)}}{Fe(OH)_3} + e^- + 3H^+ \longrightarrow \underset{\text{Fe(II)}}{Fe^{2+}} + 3H_2O \qquad (7.4)$$

When these reduction reactions proceed, soil colors change from the reds of iron oxides to the greys of reduced iron and minerals exposed by the removal of iron oxide coatings (see Figure 7.5 and Sections 4.1 and 7.7). Similar reactions involve the reduction or oxidation of C, N, Mn, S, and other elements from the solution, organic matter, and mineral components of the soil.

The E_h value at which a particular oxidation–reduction (**redox**) reaction can occur depends on the chemical to be oxidized or reduced and the pH at which the reaction takes place, as illustrated by the sloping lines in Figure 7.6. At E_h values above and below a given line, the corresponding chemical element would be found in oxidized and reduced forms, respectively. The fact that these lines are sloping downward suggests that the E_h for a reaction is lower when the pH of the soil solution is higher. Since both pH and E_h are easily measured, it is not too difficult to ascertain whether a certain reaction could occur in a given soil under specific conditions.

The order of E_h lines from the top to the bottom of Figure 7.6 illustrates the *sequence* in which the various reduction reactions are likely to occur when a well-aerated soil

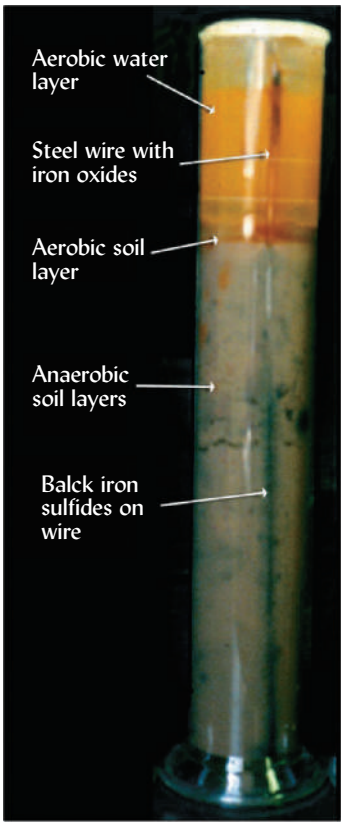

Figure 7.5 *Oxidized (orange iron oxide) and reduced (black iron sulfide) zones along a steel wire embedded in a waterlogged soil in a Winogradsky column. Soil was mixed with organic materials and calcium sulfate (to supply sulfur), blended with water to make a thick slurry and poured into a large glass cylinder such that several cm of water covered the soil which settled to the bottom. A steel wire was then inserted near the glass to act as a simple redox indicator. The cylinder was then covered with parafilm to prevent evaporation and allowed to stand in sunlight. After several weeks the action of soil microorganisms resulted in a redox gradient and the chemical changes shown.* (Photo courtesy of Ray R. Weil)

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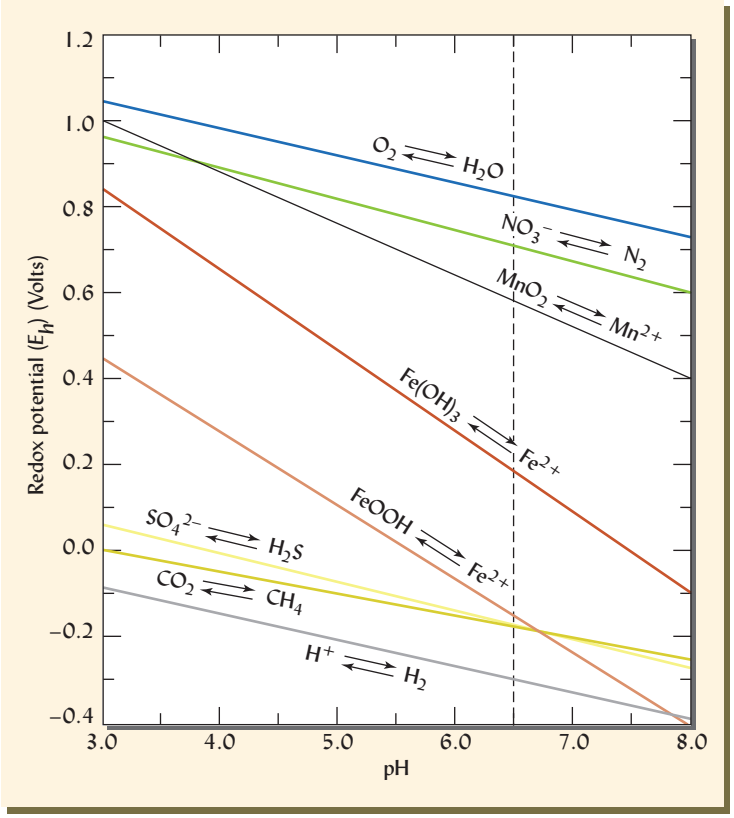

Figure 7.6 *The effect of pH on the redox potential* E_h *at which several important reduction–oxidation reactions theoretically take place. In each reaction the oxidized form of the element is on the left side and the reduced form is on the right side with the arrows indicating that the reactions can go either way. If a soil becomes saturated, the reactions will occur in order from the top down, as microorganisms first use the substances that most readily accept electrons. For example, if the pH is 6.5 (indicated by the vertical dotted line), any gaseous* O_2 *will be reduced first, followed by nitrogen* (NO_3^-)*, then manganese* (MnO_2)*, then iron in* $Fe(OH)_3$*, iron in FeOOH, and finally sulfur (in* SO_4^{2-}*) and carbon (in* CO_2*).* [Modified from McBride (1994); used with permission of Oxford University Press]

becomes saturated with water. It is important to note, however, that E_h lines are theoretical and based on the assumptions that all the *reactions are at equilibrium* and that the electrons and protons from one reaction are perfectly free to participate in any of the other reactions. In real soils, these assumptions are hardly ever met.

Table 7.1 lists oxidized and reduced forms of several elements, along with the approximate redox potentials at which the oxidation–reduction reactions were observed to actually

Table 7.1
OXIDIZED TO REDUCED FORMS AND CHARGE FOR SEVERAL ELEMENTS AND REDOX POTENTIALS E_H AT WHICH THE REDOX REACTIONS OCCUR IN A SOIL AT PH 6.5

The relative order of elements reduced is the same as in Figure 7.6, but E_h *values measured were generally lower than the theoretical values indicated in the figure. At* E_h *levels lower than about 0.38–0.32 V, microorganisms utilize elements other than oxygen as their electron acceptor.*

Element	Oxidized form	Charge on oxidized element	Reduced form	Charge on reduced element	E_h at which change of form occurs, V
Oxygen	O_2	0	H_2O	−2	0.38 to 0.32
Nitrogen	NO_3^-	+5	N_2	0	0.28 to 0.22
Manganese	Mn^{4+}	+4	Mn^{2+}	+2	0.22 to 0.18
Iron	Fe^{3+}	+3	Fe^{2+}	+2	0.11 to 0.08
Sulfur	SO_4^{2-}	+6	H_2S	−2	−0.14 to −0.17
Carbon	CO_2	+4	CH_4	−4	−0.20 to −0.28

E_h values from Patrick and Jugsujinda (1992).

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occur in a soil at pH 6.5. Because in actual soils the various reactions may be spatially separated from each other and some reaction rates are slower than others, equilibrium is rarely, if ever, achieved. Therefore, the measured E_h values for the reaction (Table 7.1) tend to be quite a bit lower than the theoretical values indicated by the lines in Figure 7.6.

Figure 7.7 provides further insights into the sequence of reduction reactions that typically occur after a soil is inundated. Once the soil becomes essentially devoid of O_2 the soil redox potential falls below levels of about 0.38–0.32 V (at pH 6.5). After O_2, the next most easily reduced substance present is usually the N^{5+} in nitrate (NO_3^-). If the soil contains much NO_3^- the E_h will remain near 0.28–0.22 V as the nitrate is reduced:

$$\underset{N(V)}{\overset{(5+)}{NO_3^-}} + 2e^- + 2H^+ \longleftrightarrow \underset{N(III)}{\overset{(3+)}{NO_2^-}} + H_2O \qquad (7.5)$$

Once all the N^{5+} in nitrate has been transformed into NO_2^-, N_2, and other N species, Mn, Fe, and S (in SO_4^{2-}) and C (in CO_2) accept electrons and become reduced, predominantly in the order shown in Figure 7.6 and Table 7.1.

In other words, transformation of different elements requires different degrees of reducing conditions. The soil E_h must be lowered to −0.2 V before methane is produced, but reduction of NO_3^- to N_2 gas takes place when the E_h is as high as +0.28 V. We can conclude that soil aeration helps determine the specific chemical species present in soils and, in turn, the availability, mobility, and possible toxicity of many chemical elements.

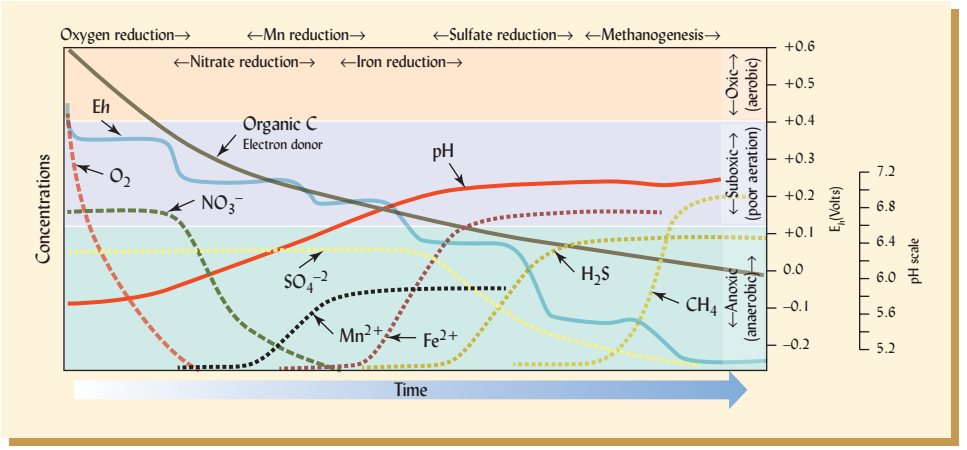

Figure 7.7 *Generalized changes in soil chemistry following water saturation of a soil with plentiful organic matter. Depending mainly on the temperature and the level of easily oxidized organic carbon present, the time period depicted could range from a few days (if warm and high in sugars) to a few weeks (if cool and low in easily oxidized C). In the first period, aerobic and facultative microorganisms digest (oxidize) the organic carbon via respiration, consuming (reducing) most of the dissolved O_2, thereby lowering the E_h of the soil solution (solid blue line). As O_2 is depleted and E_h drops, conditions become suitable for anaerobic microorganisms that can use substances in the soil solution such as nitrate (NO_3^-) as the terminal acceptor for electrons released by their metabolism. This process reduces the nitrate and lowers the E_h further. As E_h drops, microbes then reduce manganese [Mn(III,IV)] and later iron [Fe(III)] oxides in soil minerals, causing the reduced metal ions to appear in solution. Such reactions change the color of the soil by dissolving certain iron-containing minerals. As depicted by the solid red line in the graph, the pH tends to rise as H^+ ions are consumed in reactions that reduce Fe^{3+} (see reactions (7.1) and (7.4)). Once most of the iron has been reduced and the E_h has dropped well below 0 V, the S(+VI) in sulfate (SO_4^{-2}) is reduced to sulfide (S^{-2})producing hydrogen sulfide gas (H_2S). Finally, carbon compounds are reduced by certain microbes (methanogens) to produce methane gas (CH_4).* (Diagram courtesy of Ray R. Weil)

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7.4 FACTORS AFFECTING SOIL AERATION AND E_h

Drainage of Excess Water

Drainage of gravitational water out of the profile and concomitant diffusion of air into the soil takes place most readily in macropores. Soil texture, bulk density, aggregate stability, organic matter content, and biopore formation are among the soil properties that help determine macropore content and, in turn, soil aeration (see Section 4.8). Artificial drainage influences aeration by essentially creating gigantic macropores in the soil system that can rapidly carry off excess water and lower the water table (see Section 6.7).

Rates of Respiration in the Soil

The concentrations of both O_2 and CO_2 are largely dependent on microbial activity, which in turn depends on the availability of organic carbon compounds as food. Incorporation of large quantities of animal manure, crop residues, compost, or sewage sludge may alter the soil air composition appreciably. Likewise, the cycling of plant residues by leaf fall, root mass decay, and root excretion provides the main substrates for microbial activity in natural ecosystems. Respiration by plant roots and enhanced respiration by soil organisms near the roots are also significant processes. All these processes are very much enhanced as soil temperature increases (see Section 7.8).

The Soil Profile

Subsoils are usually lower in oxygen than are topsoils. Not only is the water content usually higher (in humid climates), but the total pore space, as well as the macropore space, is generally much lower in the deeper horizons. In addition, gases in deep horizons have a longer pathway for diffusion into and out of the soil than gases near the soil surface. However, the subsoil may still be aerobic because O_2 can diffuse fast enough to replace that used by respiration if organic substrates are in low supply. For this reason, certain recently flooded soils may become anaerobic in the upper 50–100 cm, but remain aerobic deeper in the soil profile.

Tree roots may extend into layers that are very low in oxygen and high in carbon dioxide, especially if the subsoil is high in clay. Carbon dioxide levels of nearly 15% (150 mL/L) have been observed in some such subsoils. Studies in deep, highly weathered soils under tropical rain forests indicate that respiration is carried out, and the concentration of CO_2 continues to rise, down into the deepest subsoil layers (Figure 7.8). Understanding the diffusion of gases up and down a soil profile is important for modeling such environmentally influential processes as the emission of gases from landfills (Figure 7.9).

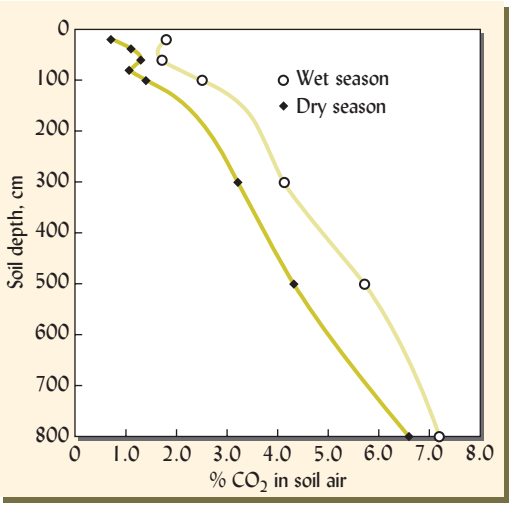

Figure 7.8 *Changes in the concentration of CO_2 in soil air with depth into the profile of a Haplustox soil under a tropical rain forest in the Brazilian Amazon region. The source of the CO_2 was likely a combination of root and microbial respiration. Although by far the highest rates of CO_2 production were in the upper soil layers, gas produced there had little distance to travel to reach the atmosphere and many large pores to travel through. The concentration of CO_2 increased with depth because the increasing travel distance to the surface and the much lower macroporosity at depth greatly slowed the movement of gases, causing CO_2 to accumulate.* [Data from Davidson and Trumbore (1995)]

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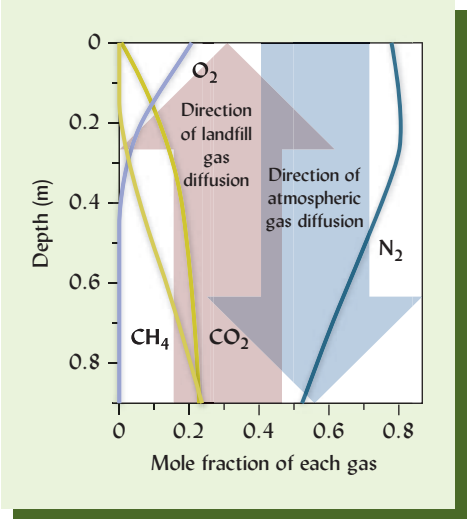

Figure 7.9 *Simulated changes in the composition of the soil air as landfill gases (methane CH_4 and carbon dioxide CO_2) diffuse up and oxygen O_2 and nitrogen N_2 diffuse down through the soil covering a landfill (see also Section 18.10). In the surface horizon (upper 20 cm) the O_2 and N_2 concentrations are similar to those in the atmosphere, but with the concentration of CO_2 rising with depth at the expense of O_2. Deeper in the soil (closer to the buried garbage) O_2 is virtually absent as it has all been respired by soil microbes, while CH_4 and CO_2 produced by microbial processes in the anaerobic decay of the garbage rise up through the soil by diffusion. In the deeper layers the N_2 concentration is reduced because of dilution by the other gases.* [Redrawn from Molins et al. (2008)]

Soil Heterogeneity

Tillage. One cause of soil heterogeneity is tillage, which has both short-term and long-term effects on soil aeration. In the short term, stirring the soil often allows it to dry out faster and also mixes in large quantities of air. These effects are especially evident on somewhat compacted, fine-textured soils, on which plant growth often responds immediately after a cultivation to control weeds or "knife in" fertilizer. In the long term, however, tillage may reduce macroporosity (see Section 4.6).

Pore Sizes. Very small pores in a clayey or compacted soil layer may also slow water percolation so that the overlying soil becomes waterlogged and poorly aerated. Such layers may also slow the diffusion of O_2 and thereby lower redox potentials within that layer, whether or not the soil is saturated. Similarly, O_2 will diffuse much more slowly through the small, largely water-filled pores within a soil aggregate than through the largely air-filled pores between aggregates. Therefore, anaerobic conditions may occur in the center of an aggregate, only a few mm from well-aerated conditions near the surface of the same aggregate (Figures 7.4, *right* and 7.10).

In some upland soils, large subsoil pores such as cracks between peds and old root channels may periodically fill with water, causing localized zones of poor aeration. This condition is expressed by gray, reduced surfaces on peds with reddish, oxidized interiors (see, e.g., Figure 4.54*d*). In a normally saturated soil, such large pores may cause the opposite effect (peds with oxidized faces but reduced interiors), as they facilitate O_2 diffusion into the soil during dry periods.

Plant Roots. Respiration by the roots of upland plants usually depletes the O_2 in the soil just outside the root. The opposite can occur in wet soils growing hydrophytic plants. Aerenchyma tissues in these plants may transport surplus O_2 into the roots, allowing some to diffuse into the soil and produce an oxidized zone in an otherwise anaerobic soil (see Section 7.7).

For all these reasons, aerobic and anaerobic processes may proceed simultaneously and in very close proximity to each other in the same soil. This heterogeneity of soil aeration should be kept in mind when attempting to understand the role that soil plays in elemental cycling and ecosystem function.

Seasonal Differences

In many soils, aeration status varies markedly with the seasons. In temperate humid regions, soils are often wet early in spring and opportunities for ready gas exchange are poor. But due

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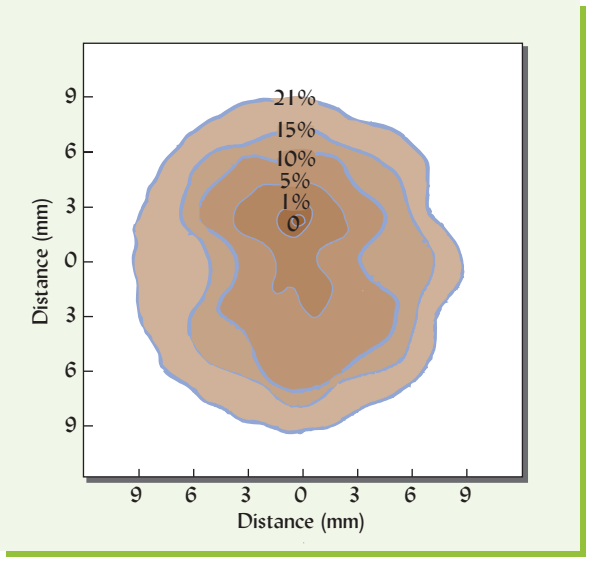

Figure 7.10 *The oxygen content of soil air in a wet aggregate in an Aquic Hapludoll (Muscatine silty clay loam) from Iowa, USA. The measurements were made with a unique microelectrode. Note that the oxygen content near the aggregate center was zero, while that near the edge of the aggregate was 21%. Thus, pockets of oxygen deficiency (anaerobic zones) can be found in a soil whose overall oxygen content may not be low. Refer also to Figure 7.4.* [Diagram from Sexstone et al. (1985)]

to low soil temperatures, the utilization of O_2 and release of CO_2 by plant roots and microorganisms is restricted. In summer, these soils are commonly lower in moisture content, and the opportunity for gas exchange is increased. However, plant roots and microorganisms, stimulated by the warmer temperatures, quickly deplete O_2 and release copious quantities of CO_2 (Figure 7.11).

Effects of Vegetation

In addition to the root respiration effects mentioned previously, vegetation may affect soil aeration by removing large quantities of water via transpiration, enough to lower the water table in some poorly drained soils.

7.5 ECOLOGICAL EFFECTS OF SOIL AERATION[2]

Effects on Organic Residue Degradation

Soil aeration influences many soil reactions and, in turn, many soil properties. The most obvious of these reactions are associated with microbial activity, especially the breakdown

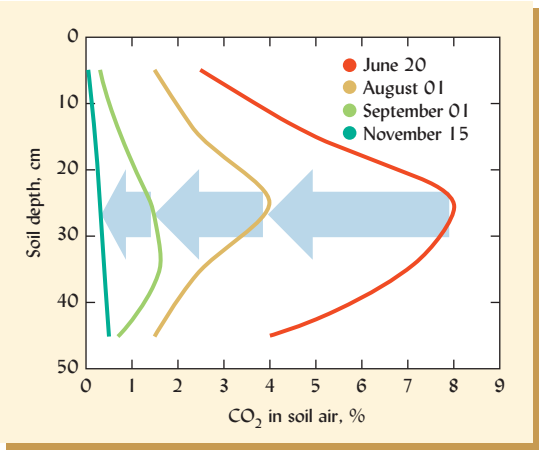

Figure 7.11 *Seasonal changes in carbon dioxide content in the upper 50 cm of an Alfisol in Missouri, USA, on which corn was grown from early May until about September 1. By June 20, the corn was growing vigorously, the soil moisture level was still quite high, and the CO_2 level increased to more than 7% in the 10- to 30-cm zone. By August 1 gaseous exchange had probably increased and the CO_2 level had declined to 3–4% in the 20- to 30-cm layer, but even this is 100 times the level in the atmosphere. By November 15 activities of plants and microorganisms had declined because of lower temperatures and the CO_2 below 20 cm was only 10 times that in the atmosphere.* [Drawn from data in Buyanovsky and Wagner (1983); used with permission of the Soil Science Society of America]

[2]For interdisciplinary reviews of the influence of soil aeration and redox reactions on plant and microbial ecology, see Husson (2012) and of how plants sense and adapt to low O_2, see Bailey-Serres et al. (2012).

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of organic residues and other microbial reactions. Poor aeration slows down the rate of decay, as evidenced by the relatively high levels of organic matter that accumulate in poorly drained soils.

The nature as well as the rate of microbial activity is determined by the O_2 content of the soil. Where O_2 is present, aerobic organisms are active, see Section 12.2. In the absence of gaseous oxygen, anaerobic organisms take over. Much slower breakdown occurs through reactions such as the following:

$$\underset{\text{Sugar}}{C_6H_{12}O_6} \rightarrow 2CO_2 + \underset{\text{Ethanol}}{2CH_3CH_2OH} \tag{7.6}$$

Poorly aerated soils therefore tend to contain a wide variety of only partially oxidized products such as ethylene gas (C_2H_4), alcohols, and organic acids, many of which can be toxic to higher plants and to many decomposer organisms. The latter effect helps account for the formation of Histosols in wet areas where inhibition of decomposition allows thick layers of organic matter to accumulate. In summary, the presence or absence of oxygen gas completely modifies the nature of the decay process and its effects on plant growth.

Oxidation–Reduction of Elements

Nutrients. The level of soil oxygen and the redox potential largely determine the forms of several inorganic elements, as shown in Table 7.2. The oxidized states of the nitrogen and sulfur are readily utilizable by higher plants. In general, the oxidized conditions are desirable for iron and manganese nutrition of most plants in acid soils of humid regions because, in these soils, the reduced forms of these elements are so soluble that toxicities may occur. In drier areas with neutral-to-alkaline soils, oxidized forms of iron and manganese are tied up in highly insoluble compounds, resulting in plant deficiencies of these elements. In these situations, restricted aeration resulting in reduced forms of elements such as iron and manganese can improve soil fertility. Some reduction of iron may also be beneficial in acid soils as it will release phosphorus from insoluble iron-phosphate compounds. Such phosphorus release has implications for eutrophication (see Section 14.2) when it occurs in saturated soils or in underwater sediments. These examples illustrate the interaction of soil E_h and pH in supplying available nutrients to plants (see Chapter 15).

Toxic Elements. Redox potential determines the species of such potentially toxic elements as chromium, arsenic, and selenium, markedly affecting their impact on the environment and food chain (see Section 18.8). Reduced forms of arsenic are most mobile and toxic, giving rise to toxic levels of this element in drinking water, a serious human health problem in many places around the world, but especially in Bangladesh. In contrast, it is the oxidized hexavalent form of chromium (Cr^{6+}) that is mobile and very toxic to humans. In neutral to acid soils, easily decomposed organic materials can be used to reduce the chromium to the less dangerous Cr^{3+} form, which is not subject to ready reoxidation (Figure 7.12).

Table 7.2
OXIDIZED AND REDUCED FORMS OF SEVERAL IMPORTANT ELEMENTS

Element	Normal form in well-oxidized soils	Reduced form found in waterlogged soils
Carbon	CO_2, $C_6H_{12}O_6$	CH_4, C_2H_4, CH_3CH_2OH
Nitrogen	NO_3^-	N_2, NH_4^+
Sulfur	SO_4^{2-}	H_2S, S^{2-}
Iron	Fe^{3+} [Fe(III) oxides]	Fe^{2+} [Fe(II) oxides]
Manganese	Mn^{4+} [Mn(IV) oxides]	Mn^{2+} [Mn(II) oxides]

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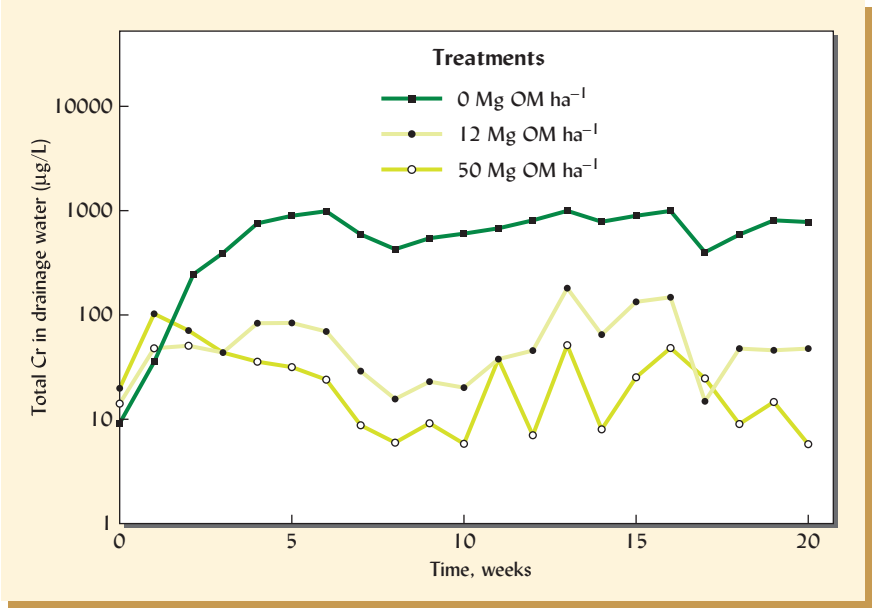

Figure 7.12 *Effect of adding decomposable organic matter (dried cattle manure) on the concentration of chromium in water draining from a chromium-contaminated soil. As the manure oxidized, it caused the reduction of the toxic, mobile Cr^{6+} to the relatively immobile, nontoxic Cr^{3+}. Note the log scale for the Cr in the water, indicating that addition of 50 Mg manure ha^{-1} caused Cr to be lowered approximately 100-fold. The coarse-textured soil was a Typic Torripsamment in California, USA.* [Data from Losi et al. (1994)]

Soil Colors. As was discussed in Section 4.1, soil color is influenced markedly by the oxidation status of iron and manganese. Colors such as red, yellow, and reddish brown are characteristic of well-oxidized conditions. More subdued shades such as grays and blues predominate if under reduced conditions. Soil color is used in the field to classify wetland soils. Soils zones of alternating oxidized and reduced conditions are characterized by contrasting small areas of oxidized and reduced materials often associated with ped interiors and ped faces. Such a "mottled" appearance indicates conditions not conducive to the optimum growth of upland plants.

Greenhouse Gases. The production of nitrous oxide (N_2O) and methane (CH_4) in wet soils is of global significance. These two gases, along with carbon dioxide (CO_2), are responsible for about 80% of the anthropogenic global warming caused by the "greenhouse effect" (see Section 12.9). The atmospheric concentrations of these gases have been increasing at alarming rates each year for the past half century or more.

Methane gas is produced by the reduction of CO_2. Its formation occurs when the E_h is −0.2 V, a condition common in natural wetlands and in rice paddies (see Figure 12.31). It is estimated that wetlands in the United States emit about 100 million metric tons of methane annually. Nitrous oxide is also produced in large quantities by wetland soils, as well as sporadically by upland soils. Because of the biological productivity and diversity of wetlands (Section 7.7), soil scientists are seeking means of managing greenhouse gases from these wetland soils without resorting to draining (i.e., destroying) them. Fortunately, it may be possible to minimize production of all three major greenhouse gases by maintaining soil E_h in a moderately low range that is feasible for many rice paddies and natural wetlands (Figure 7.13).

Effects on Activities of Higher Plants[3]

It is the lack of oxygen in the root environment rather than the excessive wetness itself that impairs plant growth in flooded or overly wet soils. This fact explains why flooding a soil with stagnant water is generally much more damaging to plants—even for some hydrophytes—than flooding with flowing water. The O_2 content of the soil is continually replenished by flowing water, but roots and microbes will completely deplete the O_2 supply under stagnant water.

[3]Drew (1990) reviews mechanisms by which plants detect and adapt to changes in O_2 in the rootzone.

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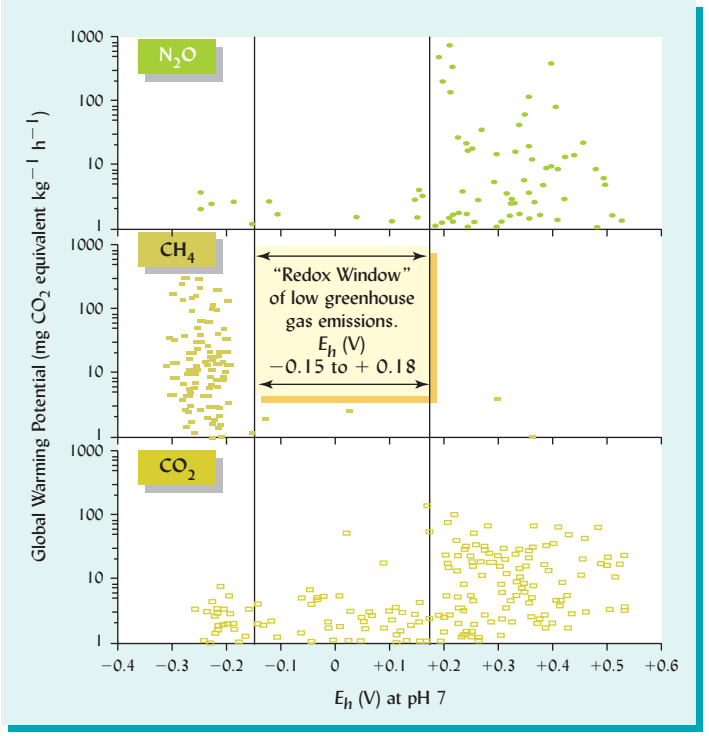

Figure 7.13 *The relationship between soil redox potentials (E_h) and emissions of three "greenhouse" gases from soils. Because the three gases differ widely in their potential for global warming per mole of gas, their emissions are expressed here as CO_2 equivalents. Note the low global warming potential from all three gases when E_h is between −0.15 and +0.18. Although this study used small containers of flooded soil in the lab, it may be desirable to manage the aeration status of flooded soils in rice paddies and wetlands with these results in mind. Manipulating organic matter additions, water table levels, water flow rates, and the duration of flooding might allow managers to maintain the soil within the "window" where E_h is too high to stimulate microbial methanogenesis (CH_4 production) but also too low to stimulate production of much N_2O or CO_2. Such management, if feasible, could potentially reduce the contribution of wet soils to global warming.* [From Yu and Patrick (2004) with permission of The Soil Science Society of America]

Plant Growth. The lack of oxygen in the soil alters root function and changes the metabolism of the entire plant. Often poor soil aeration will reduce shoot growth even more than root growth. Among the first plant responses to low soil oxygen is the closure of leaf stomata, followed by reductions in photosynthesis and sugar translocation within the plant. The ability of the root to take up water and nutrients is inhibited, and as a result of impaired root metabolism, plant hormones are thrown out of balance.

Plant species vary in their ability to tolerate poor aeration (Table 7.3). Among crop plants, sugar beet is an example of a species that is very sensitive to poor soil aeration (see Figure 7.2, *left*). At the opposite extreme, paddy rice (Figure 13.15*a*) is an example of a species that can grow with its roots completely submerged in water. Furthermore, for a given species of plant, the young seedlings may be more tolerant of low soil aeration porosity than are older plants. A case in point is the tolerance of red pine to restricted drainage during its early development and its poor growth or even death on the same site at later stages (see Figure 7.2, *right*).

The occurrence of native plants specially adapted to anaerobic conditions is useful in identifying wetland sites (see Section 7.7). Knowledge of plant tolerance to poor aeration is useful in choosing appropriate species to revegetate wet sites.

Nutrients and Water Uptake. Low O_2 levels constrain root respiration and impair root function. The root cell membrane may become less permeable to water, so that plants may actually have difficulty taking up water and some species will wilt and desiccate in a waterlogged soil. Likewise, plants may exhibit nutrient deficiency symptoms on poorly drained soils even though the nutrients may be in good supply. Furthermore, toxic substances (e.g., hydrogen sulfide or ethylene gas) produced by anaerobic microorganisms may harm plant roots and adversely affect plant growth.

Soil Compaction. Soil compaction does decrease the exchange of gases; however, the negative effects of soil compaction are not all owing to poor aeration. Soil density and strength itself can impede the root growth even if adequate oxygen is available (see Sections 4.7 and 5.9).

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Table 7.3
EXAMPLES OF PLANTS WITH VARYING DEGREES OF TOLERANCE TO A HIGH WATER TABLE AND ACCOMPANYING RESTRICTED AERATION
Certain species (left most) thrive in wetlands, while others (rightmost) are very sensitive to poor aeration.

Plants adapted to grow well with a water table at the stated depth				
<10 cm	15–30 cm	40–60 cm	75–90 cm	>100 cm
Bald cypress	Alsike clover	Birdsfoot trefoil	Beech	Arborvitae
Black spruce	Bermuda grass	Black locust	Birch	Barley
Common cattail	Black willow	Bluegrass	Cabbage	Beans
Cranberries	Cottonwood	Green ash	Corn	Cherry
Duckgrass	Creeping bentgrass	Linden	Hairy vetch	Hemlock
Phragmites grass	Deer tongue	Mulberry	Millet	Oats
Mangrove	Eastern gamagrass	Mustard	Peas	Peach
Pitcher plant	Ladino clover	Pin oak	Pecan	Sand lovegrass
Reed canary grass	Loblolly pine	Red maple	Red oak	Sugar beets
Rice	Orchard grass	Sorghum	Soybean	Walnut
Skunk cabbage	Redtop grass	Sweetgum		Wheat
Spartina grass	Tall fescue	Sycamore		White pine
Swamp white oak		Weeping love grass		
Swamp rose mallow		Willow oak		

7.6 SOIL AERATION IN URBAN LANDSCAPES

For crops in the field, aeration may be enhanced by implementing the principles outlined in Sections 4.5–4.7 regarding the maintenance of soil aggregation and tilth. Equally important are systems to increase both surface and subsurface drainage (see Section 6.7) and encourage the production of vertically oriented biopores (e.g., earthworm and root channels) that are open to the surface (Sections 4.5 and 6.7). Here we will briefly consider steps that can be taken to avoid aeration problems for container-grown plants, landscape trees, and lawns.

Container-Grown Plants

Plants grown in containers require especially careful aeration management. The root zone of containerized plants has a limited volume to store water, is exposed to fluctuations in air temperature, and lacks pore continuity to a subsoil layer. These characteristics lead potted plants to become subject to extremes of both drought and waterlogging more frequently than their in-ground counterparts (Figure 7.14). Potting soils (or *growing media*) are engineered to meet the requirements of containerized plants and minimize waterlogging. Mineral soil generally makes up no more than one-third of the volume of most potting mixes, the remainder being composed of inert, lightweight, and coarse-grained materials such as perlite (expanded volcanic glass), vermiculite (expanded mica—not soil vermiculite), or pumice (porous volcanic rock). In order to achieve maximum aeration and minimum weight, some potting mixes contain no mineral soil at all. Most modern potting soils also contain some peat, shredded bark, wood chips, compost, or other stable organic material that adds macroporosity and holds water. Some media are made up entirely of such organic materials.

Despite the fact that most planting containers have holes to allow for drainage of excess water, the bottom of the container still creates a perched water table. As is the case with stratified soils in the field (Section 5.6), water drains out of the holes at the bottom of the pot *only* once the soil at the bottom is saturated with water and the water potential is positive. Most soil pores near the bottom of the container remain filled with water, leaving no room for air, and anaerobic conditions soon prevail. The situation is aggravated if the potting medium

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Figure 7.14 *Plants grown in containers are susceptible to extremes of drought and waterlogging. Containerized soils require special management to control aeration and water, but it is easier to apply such management to soil in containers than to field soils.* (Photo courtesy of Ray R. Weil)

contains much mineral soil. In any case, the use of as tall a pot as possible will allow for better aeration in the upper part of the medium. Small, frequent applications of water should be made once the soil *near the bottom of the container* has begun to dry. Thus, feeling the soil at the surface is a poor guide to when water should be added. It is better to use a sensor probe or soil corer to determine the moisture status in the bottom 1/3 of the container.

Tree and Lawn Management

Care must be taken when transplanting trees or shrubs into compacted soils that are especially conducive to creating poorly aerated, waterlogging conditions immediately around the young roots. Figure 7.15 illustrates the right and the wrong way to transplant trees into compacted soils.

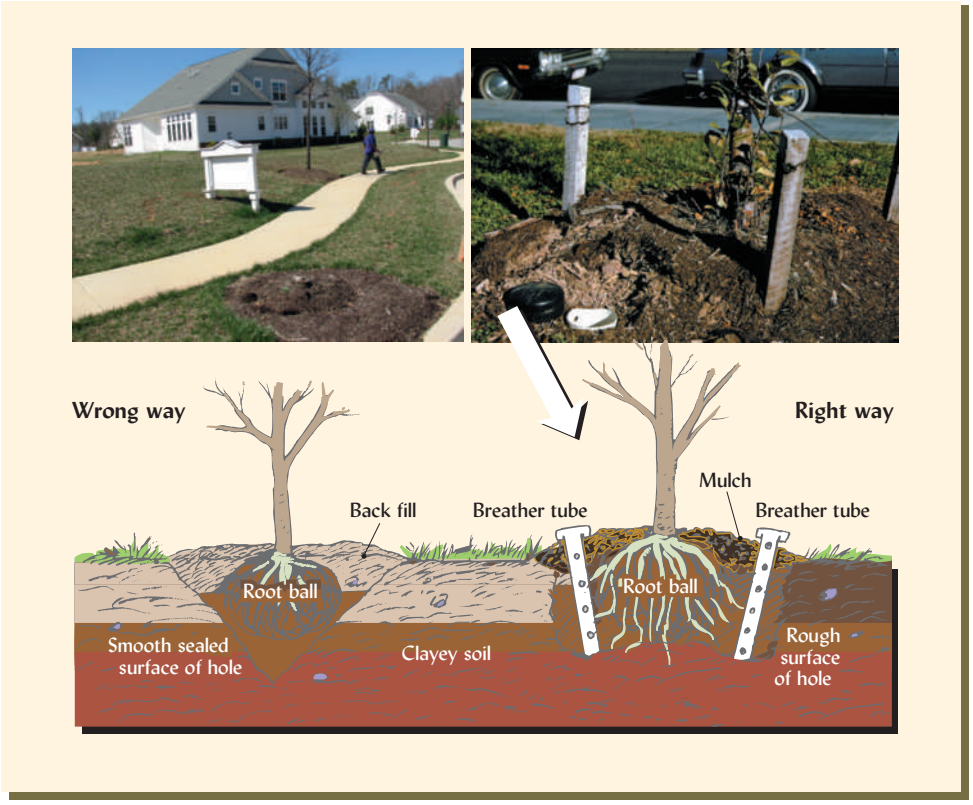

Figure 7.15 *Providing a good supply of air to tree roots can be problematic, especially when trees are planted in fine-textured, compacted soils of urban areas.* (Lower left) *A machine-dug hole with smooth sides will act as a "tea cup" and fill with water, suffocating tree roots. This was the fate of the tree in the upper left photo with only a dead stump remaining.* (Right) *Breather tubes, a larger rough-surfaced hole, and a layer of surface mulch in which some fine tree roots can grow are all measures that can improve the aeration status of the root zone.* (Photo courtesy of Ray R. Weil)

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The aeration of well-established, mature trees must also be safeguarded. If operators push surplus excavated soil around the base of a tree during landscape grading, serious consequences are soon noticed (Figure 7.16). The tree's feeder roots near the original soil surface become deficient in oxygen even if the overburden is no more than 5–10 cm in depth. One should build a protective wall (a *dry well*) or install a fence around the base of a valuable tree before grading operations begin to preserve the original soil surface and avoid compaction in a zone around the trunk, the size of the protected zone varying with the size of the tree. This measure will allow the tree's roots to continue to access the O_2 they need. Failure to observe these precautions can easily kill a large, valuable tree, although it may take a year or two to do so.

Management systems for heavily trafficked lawns commonly include the installation of perforated drainage pipes (tiles) as well as other practices that enhance soil aeration (Section 6.7). For example, ***core cultivation*** can improve aeration in compacted lawn areas. This procedure removes thousands of small cores of soil from the surface horizon, thereby permitting gas exchange to take place more easily (Figure 7.17). Spikes that merely punch holes in the soil are much less effective than corers, since compaction is increased in the soil surrounding a spike.

Figure 7.16 *Protection of valuable trees during landscape grading operations. Even a thin layer of soil spread over a large tree's root system can suffocate the roots and kill the tree.* (Left) *Therefore in the situation shown, the effort to be careful grading to preserve valuable trees is doomed to failure.* (Right) *To ensure that tree feeder roots can obtain sufficient oxygen to survive, the area immediately around the trunk should be protected by a temporary fence or a dry well may be constructed. These measures avoid compaction and preserve the original ground surface near a tree so feeder roots are not buried and suffocated. The dry well may be incorporated into the final landscape design or filled in at a rate of a few centimeters per year.* (Photos courtesy of Ray R. Weil)

Figure 7.17 *One way of increasing the aeration of compacted soil is by core cultivation. The machine removes small cores of soil, leaving holes about 2 cm in diameter and 5–8 cm deep. This method is commonly used on high-traffic turf areas. Note that the machine removes the cores and does not simply punch holes in the soil, a process that would increase compaction around the hole and impede air diffusion into the soil.* (Photos courtesy of Ray R. Weil)

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7.7 WETLANDS AND THEIR POORLY AERATED SOILS[4]

Poorly aerated areas called **wetlands** cover approximately 14% of the world's ice-free land, with the greatest areas occurring in the cold regions of Russia, Canada, and Alaska (Table 7.4). In the continental United States, about 400,000 km^2 exist today, less than half of the area that is estimated to have existed when European settlement began. Most wetland losses occurred as farmers used artificial drainage (see Section 6.7) to convert them into cropland. This conversion process was assisted by some of the same government agencies (e.g., U.S. Army Corps of Engineers and USDA) that are now working to protect wetlands from further damage. In recent decades, filling and drainage for urban development has also taken its toll on wetland areas. Since environmental consciousness has become a force in modern societies, wetland preservation has become a major issue. For example, in the United States environmental policies and laws slowed the loss of wetlands from about 200,000 ha/yr during the 1950 and 1960s, to 114,000 ha/yr during the 1970s and 1980s, 23,000 ha/yr during the early 1990s, and annual net *gains* of 12,000 ha/yr between 1998 and 2004. However, the relaxing of legal protections for wetlands and controversy over the scope of Federal government agency jurisdiction over wetlands in the early 21st century have led to increasing losses again. This mixed history is mentioned to highlight the critical role that government policy plays in determining the future of these sensitive ecosystems (Box 7.1).

Defining a Wetland[5]

Wetland is a scientific term for ecosystems that are transitional between land and water (Figure 7.19). These systems are neither strictly terrestrial (land-based) nor aquatic (water-based). While there are many different types of wetlands, they all share a key feature, namely, *soils that are water-saturated near the surface for prolonged periods when soil temperatures and other conditions are such that plants and microbes can grow and remove the soil oxygen, thereby assuring anaerobic conditions.* It is largely the prevalence of anaerobic conditions that determines the kinds of plants, animals, and soils found in these areas. There is widespread agreement that the wetter end of a wetland occurs where the water is too deep for rooted, emergent vegetation to take hold. The difficulty is in precisely defining the so-called *drier end* of the wetland, the

Table 7.4
MAJOR TYPES OF WETLANDS AND THEIR GLOBAL AREAS
All together, wetlands constitute perhaps 14% of the world's land area.

Wetland areas	Global area, 1000s km^2	Percent of ice-free land area	Percent of all wetland type
Inland (swamps, bogs, etc.)	5415	3.9	28.8
Riparian or ephemeral	3102	2.3	16.5
Organic (Histosols)	1366	1.0	7.3
Salt-affected, including coastal	2230	1.6	11.9
Permafrost-affected (Histels)	6697	4.9	35.6

Data from Eswaren et al. (1996).

[4]Two well-illustrated, nontechnical, yet informative publications on wetlands are Welsh et al. (1995) and CAST (1994). For a compilation of technical papers on hydric soils and wetlands, see Richardson and Vepraskas (2001).

[5]In 1987, the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency agreed on the following definition to be used in enforcing the Clean Water Act: "The term wetlands means those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions."

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BOX 7.1

IT'S THE LAW

Not only is it a bad idea ecologically to drain or fill wetlands, it's also against the law! In the United States and many other countries, knowingly destroying a wetland can bring severe penalties. The case reported here (Figure 7.18) reflects the change from a generation ago when most wetland destruction was caused by farmers installing agricultural drainage, to today when wetlands in industrial countries are most threatened by urban/suburban development. The newspaper reports that the developer had been informed (even warned) about the wetland area on his 1000-hectare development tract. He nonetheless filled the wetland areas so he could build hundreds of homes on these sites. To add further environmental insult, he installed septic drain fields (see Section 6.8) on these seasonally saturated soils. The judge sentenced the man to nine years in prison followed by three years of supervised release. His business partners were also imprisoned and fined. The severity of this punishment should send a message to other would-be violators.

Developers Sentenced in Wetlands Case

A federal judge sentenced three Mississippi real estate developers to prison yesterday for filling in wetlands and selling the property to low- and fixed-income families, marking the end of the nation's larg-

Figure 7.18 *Newspaper story by Eilperin (2005).* (Photo courtesy of Ray R. Weil)

Figure 7.19 *The golden brown color of hydrophytic vegetation in winter dormancy characterizes this wetland near New York City, USA. The function of wetlands as a connection between land and water is illustrated by this landscape.* (Photo courtesy of Ray R. Weil)

boundary beyond which exist upland systems in which the plant–soil–animal community is no longer predominantly influenced by the presence of anaerobic soil conditions.

The controversy is probably more political than scientific. Since use and management of wetlands are regulated by governments in many countries, billions of dollars are at stake in determining what is and what is not protected as a wetland. (Consider, e.g., a developer who wants to buy a 100-ha tract of land on which to build a shopping center. If 20 of those hectares are declared off-limits to development, how will that affect the developer's willingness to pay?)

Because so much money is at stake, thousands of environmental professionals are employed in the process of **wetland delineation**—finding the exact drier-end boundaries of wetlands on the ground. Wetland delineation is *not* done in front of a computer screen, but is a sweaty, muddy, tick- and mosquito-ridden business that those trained in soil science are uniquely qualified to carry out.

What are the characteristics these scientists look for to indicate the existence of a wetland system? Most authorities agree that three characteristics can be found in any wetland:

1. A wetland hydrology or water regime
2. Hydric soils
3. Hydrophytic plants.

We shall briefly examine each.

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Wetland Hydrology

Water Balance. Water flows into wetlands from surface runoff (e.g., bogs and marshes), from groundwater seepage, and from direct precipitation. It flows out by surface and subsurface flows, as well as by evaporation and transpiration (see Section 6.3). The balance between inflows and outflows, as well as the water storage capacity of the wetland itself, determines the elevation of the water table within or above the soil.

Hydroperiod. The temporal pattern of water table changes is termed the **hydroperiod**. For a coastal marsh, the hydroperiod may be daily, as the tides rise and fall (Figure 7.20). For inland swamps, bogs, or marshes, the hydroperiod is more likely to be seasonal. Some wetlands may be flooded for only a month or so each year, while some may never be flooded, although they are saturated within the upper soil horizons.

Also, if the period of saturation occurs when the soil is too cold for microbial or plant–root activity to take place, oxygen may be dissolved in the water or entrapped in aggregates within the soil. Consequently, true anaerobic conditions may not develop, even in flooded soils. Remember, it is the anaerobic condition, not just the saturation with water that makes a wetland a wetland.

Residence Time. The more slowly water moves through a wetland, the longer the *residence time* and the more likely that wetland functions and reactions will be carried out. For this reason, actions that speed water flow, such as creating ditches or straightening stream meanders, generally degrade a wetland and should be avoided.

Indicators. All wetlands are water-saturated some of the time, but many are not saturated all of the time. Systematic field observations, assisted by instruments to monitor the changing level of the water table, may be required to ascertain the frequency and duration of flooding or saturated conditions.

In the field, even during dry periods, there are many signs one can look for to indicate where saturated conditions frequently occur. Trees with extensive root masses above ground indicate an adaptation to saturated conditions (Figure 7.21). Past periods of flooding will leave water stains on trees and rocks and a coating of sediment on the plant leaves and litter. Drift lines of once-floating branches, twigs, and other debris also suggest previous flooding. But perhaps the best indicator of saturated conditions is the presence of **hydric soils**.

Hydric Soils[6]

In order to assist in delineating wetlands, soil scientists developed the concept of **hydric soils**. In *Soil Taxonomy* (see Chapter 3) these soils are mostly (but not exclusively) classified

Figure 7.20 *An example of a wetland with a daily hydroperiod that follows the rise and fall of the slightly brackish estuary tides. This tidal marsh with a beaver house is seen at low tide when some saturated soils and emergent plants are exposed. The drier-end boundary of the wetland is probably just beyond the treeline in the background.* (Photo courtesy of Ray R. Weil)

[6]For an illustrated field guide to features that indicate hydric soils, see Hurt et al. (1996) and Vasilas et al. (2010).

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Figure 7.21 *Above ground adventitious roots on this maple tree are one of the indicators of prolonged inundation and wetland hydrology.* (Photo courtesy of Ray R. Weil)

in the order Histosols, in Aquic suborders such as Aquents, Aquepts, and Aqualfs, or in Aquic subgroups. These soils generally have an aquic or peraquic moisture regime (see Section 3.2).

Defined. The U.S. Department of Agriculture Natural Resources Conservation Service defines a hydric soil as one "that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part." Three properties help define hydric soils. First, they are subject to *periods of saturation* that inhibit the diffusion of O_2 into the soil. Second, for substantial periods of time they undergo *reduced conditions* (see Section 7.3); that is, electron acceptors other than O_2 are reduced. Third, they exhibit certain features termed *hydric soil indicators.* Such indicators result from the reduced conditions and are discussed in Box 7.2.

Hydrophytic Vegetation

Although the vast majority of plant species cannot thrive in conditions characteristic of wetlands, there are varied and diverse communities of plants that have evolved special mechanisms to adapt to life in saturated, anaerobic soils. These plants comprise the **hydrophytic vegetation** that distinguishes wetlands from other systems.

Typical adaptive features include hollow aerenchyma tissues that allow plants like spartina grass to transport O_2 down to their roots. Certain trees (such as bald cypress and mangrove) produce adventitious roots, buttress roots, "knees" or **pneumatophores** (see Figures 7.1 and 7.21). Other species spread their roots in a shallow mass on or just under the soil surface, where some O_2 can diffuse even under a layer of ponded water. The leftmost column in Table 7.3 lists a few common hydrophytes. Not all the plants in a wetland are likely to be hydrophytes, but most usually are.

Wetland Chemistry

The central characteristic of wetland chemistry is the low redox potential (see Section 7.3) that pertains. Furthermore, many wetland functions depend on *variations* in the redox potential; that is, in certain zones or for certain periods of time oxidizing conditions alternate with reducing ones.

Low Oxygen. For example, even in a flooded wetland, O_2 will be able to diffuse from the atmosphere or from oxygenated water into the upper 1 or 2 cm of soil, creating a thin *oxidizing zone* (see Figure 7.24). The diffusion of O_2 within the saturated soil is extremely limited, so that a few centimeters deeper into the profile, O_2 is eliminated and the redox potential becomes low enough for reactions such as nitrate reduction to take place. The close proximity

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BOX 7.2

HYDRIC SOIL INDICATORS

Hydric soil indicators are features associated (sometimes only in specific geographic regions) with the occurrence of saturation and reduction. Most of the indicators can be observed in the field by using a tiling spade to dig a slice of soil to a depth of 30 cm. They principally involve the loss or accumulation of various forms of Fe, Mn, S, or C. The carbon (organic matter) accumulations are most evident in Histosols, but thick, dark-surface layers in other soils can also be indicators of hydric conditions in which organic matter decomposition has been inhibited (Figure 7.22).

Iron, when reduced to Fe(II), becomes sufficiently soluble that it migrates away from reduced zones and may precipitate as Fe(III) compounds in more aerobic zones. Zones where reduction has removed the iron coatings from mineral grains are termed ***redox depletions.*** They commonly exhibit the gray, low-chroma colors of the bare, underlying minerals (see Section 4.1 for an explanation of chroma). Also, iron itself turns to gray or blue-green when reduced. The contrasting colors of redox depletions or reduced iron and zones of reddish oxidized iron result in unique mottled **redoximorphic features** (see, e.g., Figures 4.2 and 4.6). Other redoximorphic features involve reduced Mn. These include the presence of hard black *nodules* that sometimes resemble shotgun pellets. Under severely reduced conditions the entire soil matrix may exhibit low-chroma colors, termed gley. Colors with a chroma of 1 or less quite reliably indicate reduced conditions (Figure 7.23).

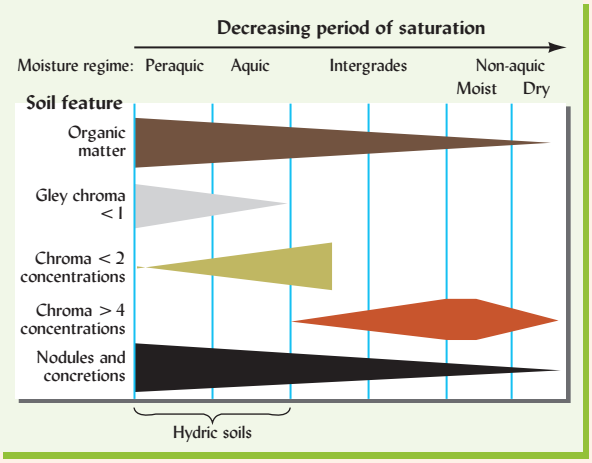

Figure 7.23 *The relationship between the occurrence of some soil features and the annual duration of water-saturated conditions. The absence of iron concentrations (mottles) with colors of chroma >4 and the presence of strong expressions of the other features are indications that a soil may be hydric. Peraquic refers to a moisture regime in which soils are saturated with water throughout the year. For other moisture regimes, see Section 3.2.* [Adapted from Veneman et al. (1999)]

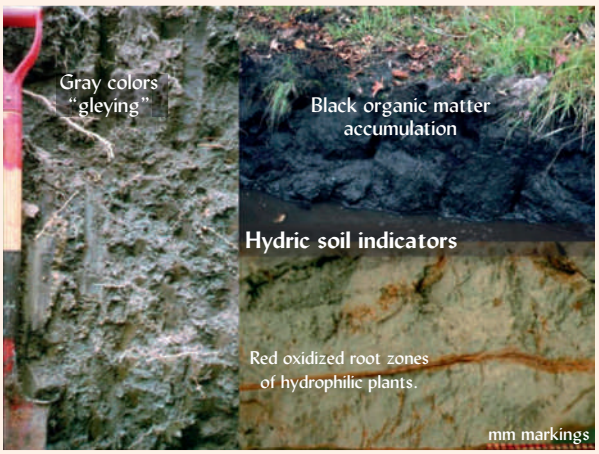

Figure 7.22 *Wetlands characteristically have hydric soils which can be recognized as such by the presence of certain features considered to be hydric soil indicators. Three of the most common of these indicators are shown here: a gleyed (iron depleted) soil matrix with low chroma gray colors; a thick, black accumulation of organic matter; and reddish oxidized coatings on roots and root channels made by the influence of oxygen transported into the soil by aerenchyma on hydrophytic plants.* (Photos courtesy of Ray R. Weil)

Always keep in mind that redoximorphic features are indicative of hydric soils only when these features occur in the upper horizons. Many soils of upland areas exhibit redoximorphic features only in their deeper horizons, due to the presence of a fluctuating water table at depth. Upland soils that are saturated or even flooded for short periods, especially if during cold weather, are not wetland (hydric) soils.

A unique redoximorphic feature associated with certain wetland plants is the presence, in an otherwise gray matrix, of reddish oxidized iron around root channels where O_2 diffused out from the aerenchyma-fed roots of a hydrophyte (see Figure 7.22). These *oxidized root zones* exemplify the close relationship between hydric soils and hydrophytic vegetation.

Although identifying hydric soils can be difficult and require a good deal of field experience, the following set of simple questions can be useful in many situations. First, look around to assess if the soil is located in or near an inundated swamp or marsh, or in a flood plain or depression. Examine a spadeful of soil about 18 cm deep (not including any O horizons consisting of identifiable plant litter. If near a coastal marsh, can you detect the rotten egg odor of hydrogen sulfide (whiff test, see Figure 13.43) Using a Munsell color book, can you see features with chroma <2? Does the soil exhibit easily visible (distinct or prominent) redox concentrations as concretions, pore linings, root traces, or ped faces? Does the soil exhibit layers of smooth black (mucky) organic material? If none of the just mentioned features exist, the soil is probably not hydric.

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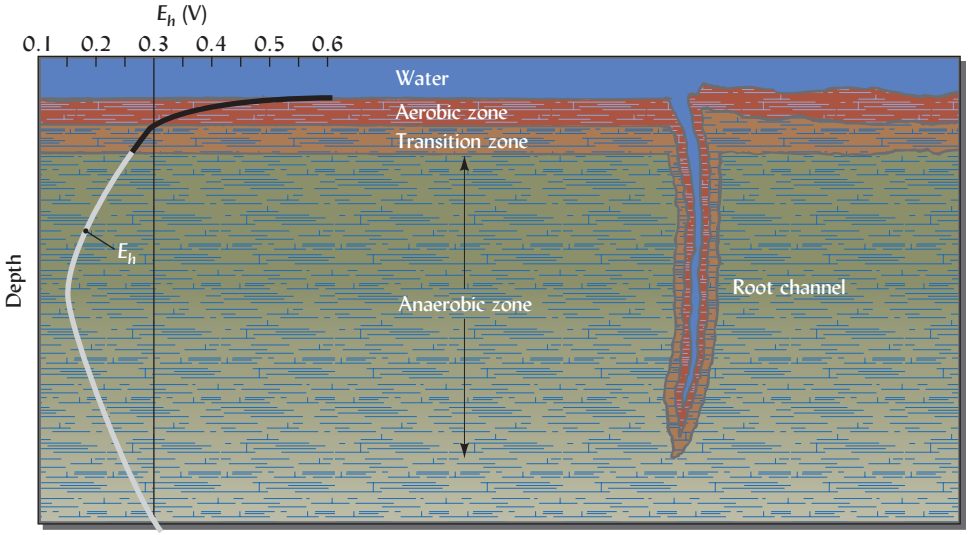

Figure 7.24 *Representative redox potentials within the profile of an inundated hydric soil. Many of the biological and chemical functions of wetlands depend on the close proximity of reduced and oxidized zones in the soil. The changes in redox potential at the lower depths depend largely on the vertical distribution of organic matter. In some cases, low subsoil organic matter results in a second oxidized zone beneath the reduced zone.*
(Diagram courtesy of Ray R. Weil)

of oxidized and anaerobic zones allows water passing through wetlands to be stripped of N as the ammonium N is oxidized to nitrate N, and the nitrate is then reduced to various nitrogen gases that escape into the atmosphere (see Section 13.9).

Redox. To be considered a wetland, redox potentials should become low enough for iron reduction to produce redoximorphic features. When E_h is even lower, sulfate reduction will produce rotten egg–smelling hydrogen sulfide (H_2S) gas. The anaerobic zone may extend downward or in some cases may be limited to the upper horizons where microbial activity is high. The anaerobic carbon reactions discussed in Section 7.5 are characteristic of this zone, including methane (swamp gas) production. These and other chemical reactions involving the cycling of C, N, and S are explained in Sections 12.2, 13.9, and 13.20. Toxic elements such as chromium and selenium undergo redox reactions that may help remove them from the water before it leaves the wetland. Acids from industry or mine drainage may also be neutralized by reactions in hydric soils. This array of unique chemical reactions contributes greatly to the benefits that society and the environment gain from wetlands (see Box 7.3).

Constructed Wetlands

Realizing all the beneficial functions of wetlands, scientists and engineers have begun not only to find ways to preserve natural wetlands, but to construct artificial ones for specific purposes, such as wastewater treatment (see, e.g., Box 14.2).

Another reason for attempting to construct wetlands is the provision in several regulations that allows for the destruction of certain natural wetland areas, provided that an equal or larger area of new wetlands is constructed or that previously degraded wetlands are restored. In some cases, wetland banks are established (Figure 7.25) where a developer can invest in the construction of new wetlands to mitigate against the loss of other wetlands destroyed or degraded by drainage or urban development. As would be expected, this process, termed ***wetland mitigation***, has been only partially successful in terms of function, as scientists cannot be expected to create what they do not fully understand.

We have seen how greatly soil aeration is influenced by soil water. We will now turn our attention to soil temperature, another physical soil property that is closely related to both soil water and aeration.

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Figure 7.25 *A wetland bank in Virginia, USA, where developers can pay to have new areas of wetlands created in order to mitigate for the destruction or degradation of wetlands by a development project. Usually, the wetlands created must be of the same type (freshwater or marsh) and in the same water shed as the destroyed wetlands.* (Photos courtesy of Ray R. Weil)

BOX 7.3

WETLAND FUNCTIONS OF VALUE TO ECOSYSTEMS AND SOCIETY

Once considered to be nothing but disease-breeding wastelands, wetlands are now widely recognized as performing many extremely valuable functions. In fact, a group of scientists and economists (Costanza et al., 1997) has estimated that on average, one hectare of wetlands provides nonmarket services worth about 15 times more than those provided by one hectare of forestland. Globally, wetlands annually perform needed ecosystem services that would cost some $13 trillion (in 2013 dollars) to replace. We can summarize at least six types of benefits derived from wetlands, the recognition of which has motivated the intensification of wetland study and protective regulation.

1. *Species habitat*. Wetlands provide special environmental conditions required by a wide array of wild species. Plants like bald cypress trees and pitcher plants, and animals like salamanders and muskrats, use wetlands as their primary habitat (i.e., they live in wetlands). Furthermore, about 40% of all endangered and threatened species depend on wetlands in some way (e.g., for food or shelter). About one-third of all bird species also depend on wetlands (Figure 7.26).
2. *Water filtration*. Water is filtered and purified as it passes through wetlands on its way from the land to rivers, bays, lakes, estuaries, and groundwater aquifers. Wetlands physically filter out most sediment, remove a high proportion of plant nutrients (especially N and P) that could otherwise cause eutrophication of aquatic systems (see Section 14.2), and break down many organic substances that could cause toxic effects or deplete O_2 supplies in aquatic systems and drinking water.
3. *Flooding reduction*. Wetlands act as giant reservoirs to hold back large volumes of stormwater runoff from the land. They then release the water slowly, either to surface flow or to groundwater, thereby avoiding high peak flows that lead to floods and damage to homes and developed land along rivers. Studies have shown that floods are far less severe and less frequent where river systems have been allowed to retain their undisturbed wetlands.
4. *Shoreline protection*. Coastal wetlands serve as a buffer between high-energy ocean waves and the shore, preventing the rapid shoreline erosion that is observed when the wetlands are drained or filled in.

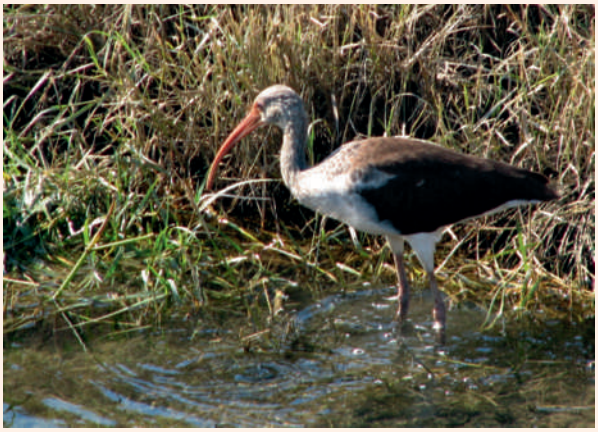

Figure 7.26 *Wetland habitats are rich in plant and animal species, many uniquely adapted to life in association with inundated soils. The soils and vegetation promote processes that remove nutrients, sediments, and contaminants from water moving slowly through the wetland.* (Photo courtesy of Ray R. Weil)

5. *Commercial and recreational activities*. In many parts of the world, people spend a great deal of money every year to catch, hunt, view, or photograph birds, animals, and fish that either live in wetlands or depend on wetlands for their food supply or for nesting sites. As a result, some of the first and most ardent proponents of wetland conservation have been organizations devoted to duck hunting or fishing.
6. *Natural products*. Valuable products such as timber, blueberries, cranberries, fish, and wild rice can be sustainably harvested from certain wetlands under careful management. Scenic beauty could also be considered a natural product of wetlands that people can enjoy without damaging the system.

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7.8 PROCESSES AFFECTED BY SOIL TEMPERATURE

The temperature of a soil greatly affects the physical, biological, and chemical processes occurring in that soil and in the plants growing on it (Figure 7.27).

Plant Processes

Most plants are actually more sensitive to *soil* temperature than to aboveground *air* temperature, but this is not often appreciated since air temperature is more commonly measured.

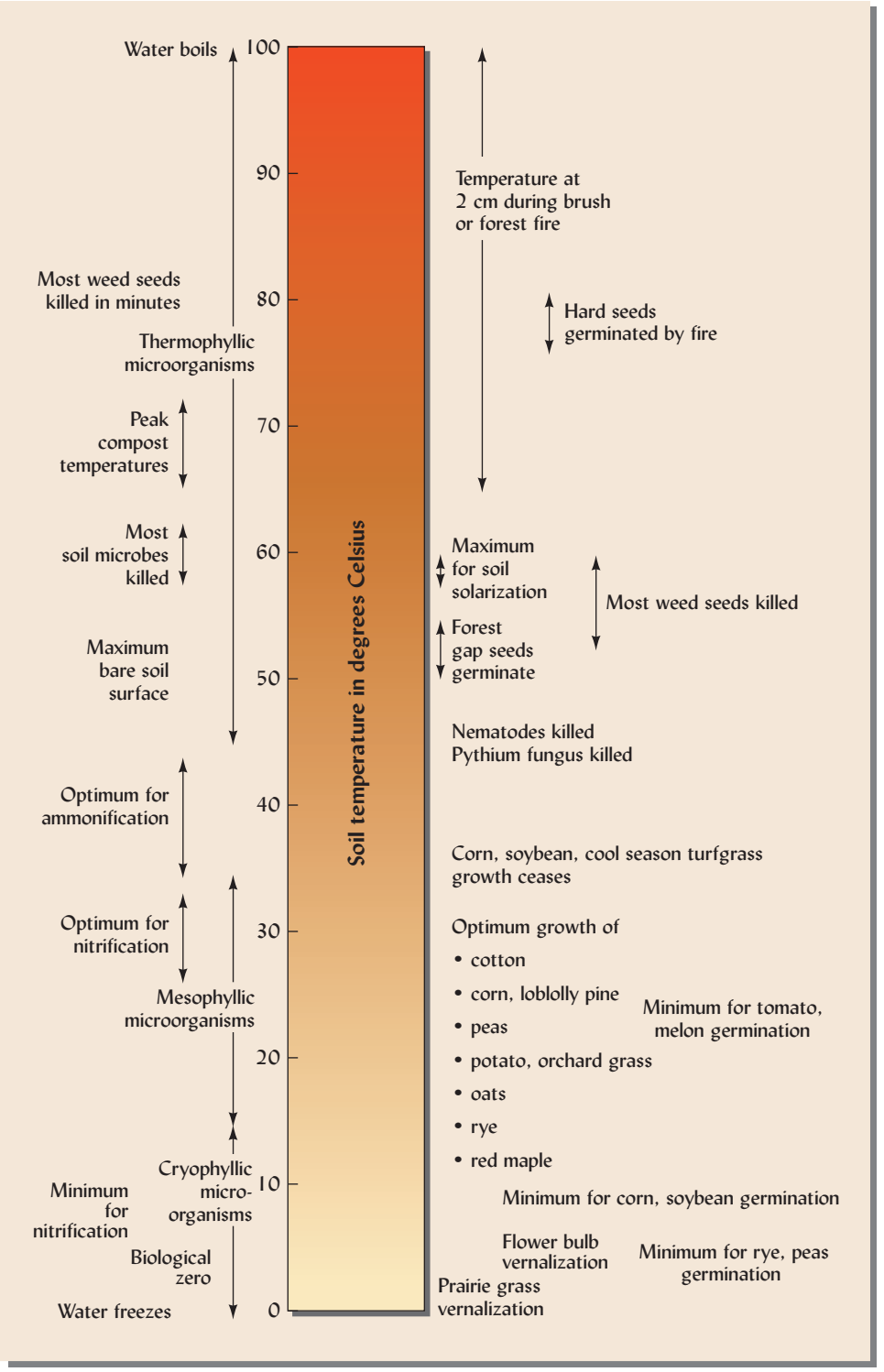

Figure 7.27 *Soil temperature ranges associated with a variety of soil processes.* (Diagram courtesy of Ray R. Weil)

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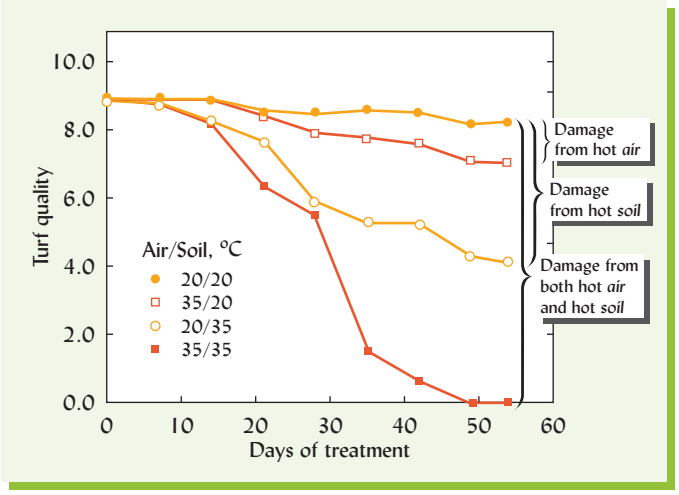

Figure 7.28 *Effects of air and soil temperatures on turfgrass quality. Heat stress is a major problem for bent grass* (Agrostis spp.) *grown on golf greens in warmer climates. Researchers in this study grew bent grass for 60 days while controlling both soil and air temperatures. Turfgrass quality (color, vigor, etc.) was rated from 0 (dead) to 10 (best quality). Compare the small decline in turf quality caused by increasing air temperature from 20 to 35 °C to the much greater decline caused by the same increase in soil temperature. High temperature in both air and soil caused the worst effects. Among the plant parameters measured, photosynthesis was affected more than root growth by soil temperature. Other research has shown that a fine spray of water combined with a large fan can cool both air and soil on a golf green.* [From Xu and Huang (2000)]

Research also shows that, contrary to what one might expect, adverse soil temperature generally influences shoot growth and photosynthesis more than root growth (as was seen in the study described in Figure 7.28). Most plants have a rather narrow range of soil temperatures for optimal growth. For example, two species that evolved in warm regions, corn and loblolly pine, grow best when the soil temperature is about 25–30 °C. In contrast, the optimal soil temperature for cereal rye and red maple, two species that evolved in cool regions, is in the range of 12–18 °C. Different plant processes for the same plant may also have different optimal temperatures; root growth is commonly optimized at lower soil temperatures than is shoot growth. For example, the optimum soil temperature ranges for root and shoot growth of corn are about 23–25 and 25–30 °C, respectively.

In temperate regions, cold soil temperature often limits the productivity of crops and natural vegetation. In these regions, artificial soil warming by underground electric wires or warm water pipes can markedly increase crop yields, but the economic and environmental viability of the practice depends on the value of the additional crops produced and the costs and environmental impacts of generating the energy used to heat the soil. The life cycles of plants are also greatly influenced by soil temperature. For example, tulip bulbs require chilling in early winter to develop flower buds, although flower development is suppressed until the soil warms up the following spring.

In warm regions, and in the summer in temperate regions, soil temperatures may be too high for optimal plant growth, especially in the upper few centimeters of soil. For example, bent grass, a cool-season grass prized for providing an excellent "playing surface" on golf greens, often suffers from heat stress when grown in warmer regions (Figure 7.28). Even plants of tropical origin, such as corn and tomato, are adversely affected by soil temperatures higher than 35 °C. Seed germination may also be reduced by high soil temperatures. In hot conditions, root growth near the surface may be encouraged by shading the soil with live vegetation, plant residues, or organic mulch.

Seed Germination. Many plants require specific soil temperatures to trigger seed germination, accounting for much of the difference in species between early- and late-season weeds in cultivated land. Likewise, the seeds of certain plants adapted to open gaps in a forest stand are stimulated to germinate by the greater fluctuations and maximum soil temperatures that occur where the forest canopy is disturbed by timber harvest or wind-thrown trees. The seeds of certain prairie grasses and grain crops require a period of cold soil temperatures (2–4 °C) to enable them to germinate the following spring, a process termed *vernalization*.

Root Functions. Root functions such as nutrient uptake and water uptake are sluggish in cool soils with temperatures below the optimum for the particular species. One result is that nutrient deficiencies, especially of phosphorus, often occur in young plants in early spring, only to disappear when the soil warms later in the season. The phenomenon of *winter*

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Figure 7.29 *Winter burn on ornamental holly trees. The leaves on these evergreen trees exhibit necrosis caused by desiccation. During bright sunny winter days evaporative demand was high but cold soil temperatures inhibited root activity such that uptake of water could not meet that demand. Winter burn can result in the death of the plant. Covering evergreen shrubs with shade cloth can prevent such damage.* (Photos courtesy of Ray R. Weil)

burn of plant foliage is another consequence of low soil temperature that particularly affects evergreen shrubs (Figure 7.29). On bright, sunny days in winter and early spring when the soil is still cold, evergreen plants may become desiccated and even die because the slow water uptake by roots in the cold soils cannot keep up with the high evaporative demand of bright sun on the foliage. The problem can be prevented by covering the shrubs with a shade cloth.

Microbial Processes

Microbial processes are influenced markedly by soil temperature changes (Figure 7.30). Although it is commonly assumed that microbial activity ceases at temperatures that freeze water (<0 °C), low rates of soil microbial activity and organic matter decomposition have been measured in the permafrost layers of Gelisols at temperatures as low as −20 °C. In fact, given that some 80% of the Earth's biosphere is colder than 5 °C, it should not be surprising that microbes have widely adapted to life at cold temperatures.

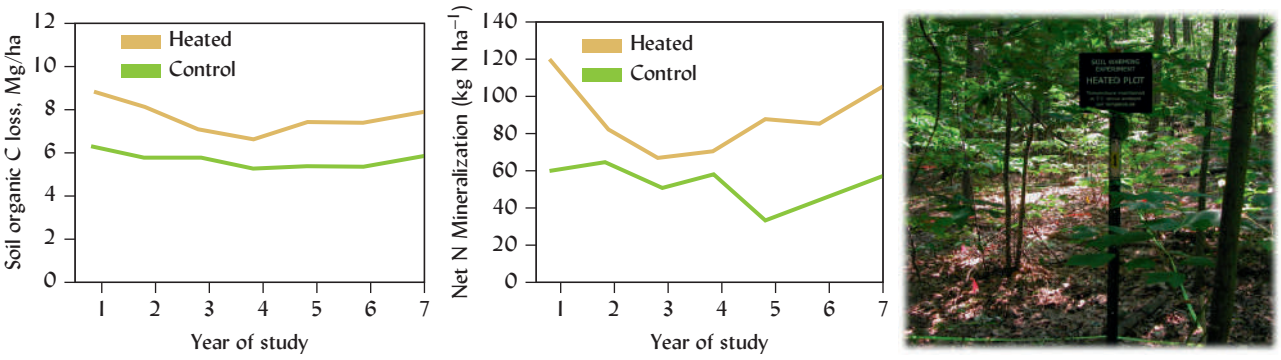

Figure 7.30 *Elevated soil temperature accelerates biological processes, such as* (upper graph) *nitrogen release from organic matter by mineralization and* (lower graph) *carbon dioxide release by soil microorganisms respiring organic matter. In this mid-latitude hardwood forest, electric heating cables were buried in certain plots to maintain soil temperature at 5° C above normal throughout the year. Cables were also installed in the control plots (photo) to assure an equal degree of physical disturbance, but no electricity was applied. The biological processes represented are discussed in detail in Chapters 12 and 13.* [Graphs from data in Melillo et al. (2011); photo courtesy of Ray R. Weil]

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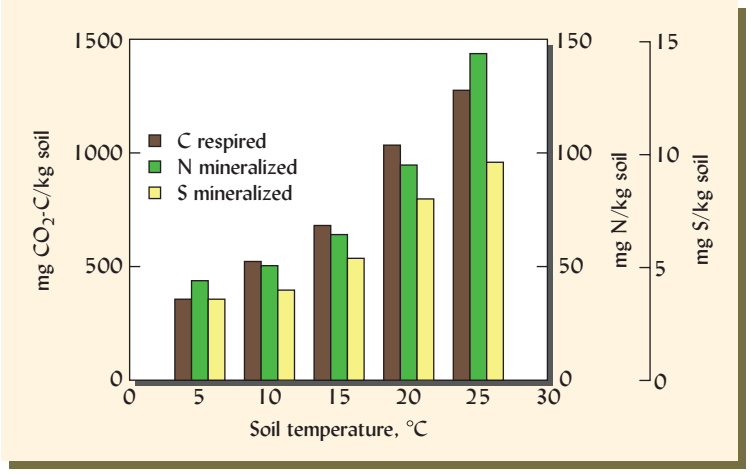

Figure 7.31 *Effect of soil temperature on cumulative microbial respiration (CO_2 release) and net nitrogen and sulfur mineralization in surface soils from hardwood forest in Michigan, USA. The soil water content was adequate for microbial growth throughout the 32-week study period. Note the near doubling of the microbial activity with a 10-degree change in soil temperature (compare findings for 15 vs. 25 °C). Means from four sites are shown.* [From MacDonald et al. (1995)]

Nonetheless, microbial activity is far greater at warm temperatures; the rates of microbial processes such as respiration typically more than double for every 10 °C rise in temperature (see Figure 7.31). The optimum temperature for microbial decomposition processes may be 35–40 °C, considerably higher than the optimum for plant growth. The dependence of microbial respiration on warm soil temperatures has important implications for soil aeration (see Section 7.7) and for the decomposition of plant residues and, hence, the cycling of the nutrients they contain. The productivity of northern (boreal) forests is probably limited by the inhibiting effect of low soil temperatures on microbial recycling and release of nitrogen from the tree litter and soil organic matter.

The microbial oxidation of ammonium ions to nitrate ions, which occurs most readily at temperatures near 30 °C, is also negligible when the soil temperature is low, below about 8–10 °C. Farmers in cool regions can take advantage of this fact by injecting ammonia fertilizers into cold soils in the early spring, expecting that ammonium ions will not be readily oxidized to leachable nitrate ions until the soil temperature rises. Unfortunately, in some years a warm spell allows the production of nitrates earlier than expected, with the result that much nitrate is lost by leaching, to the detriment of both the farmer and the downstream water quality.

In environments with hot, sunny summers (maximum daily air temperatures >35 °C) a heating process called ***soil solarization*** can be used to control pests and diseases in some high-value crops. In this process, the ground is covered with a clear plastic film that traps enough heat to raise the temperature of the upper few centimeters of soil to as high as 50–60 °C. Such high temperatures can effectively suppress certain fungal pathogens, weed seeds, and insect pests.

As we shall see in Chapter 18, warm soil temperatures are also critical for new pollution remediation technologies that utilize specialized microorganisms to degrade petroleum products, pesticides, and other organic contaminants in soils.

Freezing and Thawing

When soil temperatures fluctuate above and below 0 °C, the water in the soil undergoes cycles of freezing and thawing. Alternate freezing and thawing subject the soil aggregates to pressures as zones of pure ice, called *ice lenses*, form within the soil and as ice crystals form and expand.[7] These pressures alter the physical structure of the soil. In a saturated soil with a puddled structure, the frost action breaks up the large masses and greatly improves

[7]The pressure is due mainly to ice lens growth rather than to the 9% increase in volume that water undergoes when it freezes. Ice lenses grow as water is drawn to the freezing zone from adjacent unfrozen areas. The flow to the growing ice lenses is encouraged by the fact that fine soil particles remain coated with a film of liquid (unfrozen) water at temperatures below the normal freezing point. The lowered freezing point occurs for two reasons: (1) the influence of water–solid interactions near the particle surface, and (2) the presence of dissolved and exchangeable ions in this film of water. For details, see Torrance and Schellekens (2006).

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granulation. In contrast, for soils with good aggregation to begin with, freeze–thaw action when the soil is very wet can lead to structural deterioration. When the surface of a frozen soil thaws, the upper few mm may be completely saturated with water, making it easy for spring rains to detach soil particles that are then easily removed by erosion. In some soils of temperate regions more than 50% of the annual erosion losses take place from thawing soils.

Alternate freezing and thawing can force objects upward in the soil, a process termed ***frost heaving***. Objects subject to heaving include stones, fence posts, and perennial tap-rooted plants (Figure 7.32). This action, which is most severe where the soil is silty in texture, wet, and lacking a covering of snow, vegetative mulch or dense vegetation, can drastically reduce stands of perennial tap-rooted legumes.

Freezing can also heave shallow foundations, roads, and runways that have fine material as a base. Gravels and pure sands are normally resistant to frost damage, but silts and sandy soils with modest amounts of finer particles are particularly susceptible. Very clay-rich soils do not usually exhibit much frost heave, but ice-lens segregation can still occur and can lead to severe loss of strength when thawing occurs. To avoid damage by freezing soil temperatures, foundation footings (as well as water pipelines) should be set into the soil below the maximum depth to which the soil freezes—a depth that ranges from less than 10 cm in subtropical zones, such as South Texas and Florida in the United States, to more than 200 cm in very cold climates.

Permafrost[8]

Perhaps the most significant global event involving soil temperatures is the thawing in recent years of some of the permafrost (permanently frozen ground) in northern areas of Canada, Russia, Iceland, China, Mongolia, and Alaska. Nearly 25% of the land areas of the Earth are underlain by permafrost. Rising temperatures since the late 1980s have caused some of the

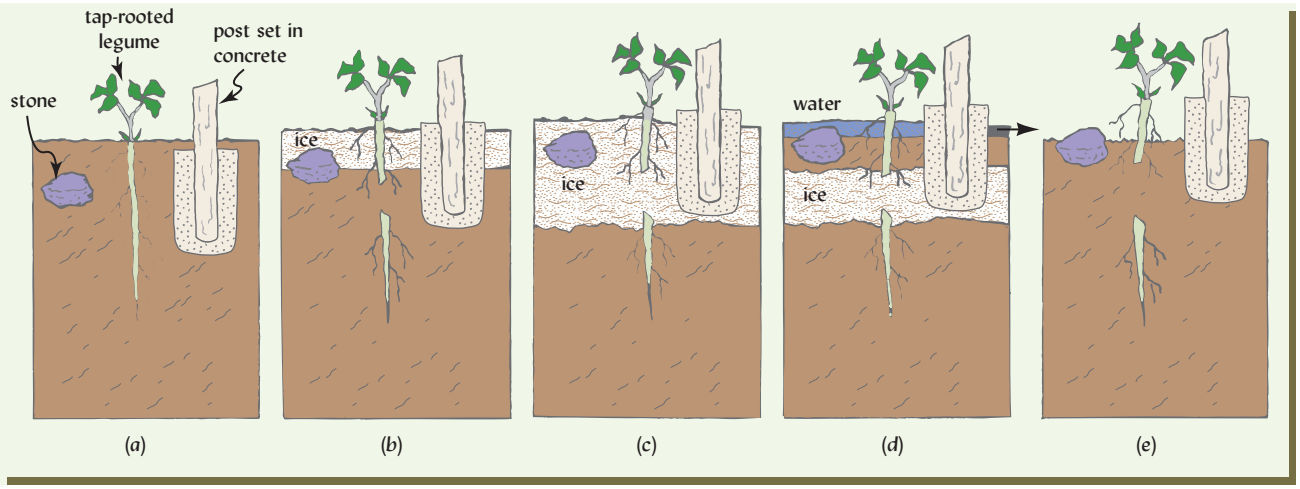

Figure 7.32 *How frost heaving moves objects upward.* (a) *Position of the object (stone, plant, or fence post) before the soil freezes.* (b) *As lenses of pure ice form in the freezing soil by attraction of water from the unfrozen soil below, the frozen soil tightens around the upper part of the object, lifting it somewhat—enough to break the root in the case of the plant.* (c) *The objects are lifted upward as ice-lens formation continues with deeper penetration of the freezing front.* (d) *As for freezing, thawing commences from the surface downward. Water from thawing ice lenses escapes to the surface because it cannot drain downward through the frozen soil. The soil surface subsides while the heaved objects are held in the "jacked-up" position by the still-frozen soil around their lower parts.* (e) *After complete thaw, the stone is closer to the surface than previously (although rarely at the surface unless erosion of the thawed soil has occurred), and the upper part of the broken plant's root is exposed, so that is likely to die.* (Diagram courtesy of Ray R. Weil)

[8]For a discussion of permafrost in Alaska, see Wuethrich (2000).

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upper layers of permafrost to thaw. In parts of Alaska, for example, temperatures in top layers of permafrost have risen about 3.5 °C since the late 1980s, resulting in melting rates of about a meter in a decade. Such melting has serious implications since it can drastically affect the physical foundation of buildings and roads, as well as the stability of root zones of forests and other such vegetation in the region. Trees fall and buildings collapse as the frozen layers melt. The thawing of arctic permafrost is expected to further accelerate global warming, as decomposition of organic materials long trapped in the frozen layers of Histels releases vast quantities of carbon dioxide into the atmosphere (see Figure 3.19).

Soil with ice lenses may contain much more water than would be needed to saturate the soil in the unfrozen state. When the ice lenses thaw, the soil becomes supersaturated because the excess water cannot drain away through the underlying still-frozen soil. Soil in this condition readily turns into noncohesive mud that is very susceptible to erosion and movement by mudslides.

Soil Heating by Fire

Fire is one of the most far-reaching ecosystem disturbances in nature. In addition to the obvious aboveground effects of forest, range, or crop-residue fires, the brief but sometimes dramatic changes in soil temperature also may have lasting impacts below ground. Unless the fire is artificially stoked with added fuel, the temperature rise from wildfires is usually very brief and is limited to the upper few centimeters of soil. But the temperatures resulting from "slash and burn" practices in the tropics (see Section 20.7) may be sufficiently high in the upper few mm of soil to cause the loss of nearly all organic natter and even the breakdown of minerals such as gibbsite and kaolinite.

The heat from wildfires may also cause the breakdown and movement of organic compounds, especially in sandy soils (Figure 7.33). The high temperatures (>125 °C being common) essentially distill certain fractions of the organic matter, with some of the volatilized hydrocarbon compounds moving quickly through the soil pores to deeper, cooler areas. As these compounds reach cooler soil particles deeper in the soil, they condense (solidify) on the surface of the soil particles and fill some of the surrounding pore spaces. Some of the condensed compounds are water-repellent (hydrophobic) hydrocarbons. Consequently, when rain comes, water infiltration in such burned over sandy soil may be greatly reduced in comparison to unburned areas. This effect of soil temperature is quite common on pine forest and chaparral lands in semiarid regions and may be responsible for the disastrous mudslides that occur when the layer of soil above the hydrophobic zone becomes saturated with rainwater (see Figure 7.33*d*).

Fires also affect the germination of certain seeds, which have hard coatings that prevent them from germinating until they are heated above 70–80 °C. The burning of straw in wheat fields generates similar soil temperatures, but with the effect of killing most of the weed seeds near the surface and thus greatly reducing subsequent weed infestation. The heat and ash from low intensity fires may also hasten the cycling of plant nutrients. In fact, grassland fires often stimulate plant regrowth so much that soil organic matter increases with fire as the enhanced plant biomass more than compensates for the loss of soil organic matter during the fire. On the other hand, fires set to clear land of timber slash may burn long and hot enough to seriously deplete soil organic matter and kill so many soil organisms that forest regrowth is inhibited.

Contaminant Removal

The removal of certain organic pollutants from contaminated soils can be accomplished by raising the soil temperature, causing the offending compounds to volatilize and diffuse out of the soil in the gaseous state. The process may be prohibitively expensive if the soil has to be excavated and hauled to and from a heated extraction facility. Techniques are under development to warm the soil in place in the field using electromagnetic radiation. The resulting temperatures are sufficiently high to vaporize some contaminants, such as toxic components in diesel fuel, which can then be flushed from the soil by a stream of injected air.

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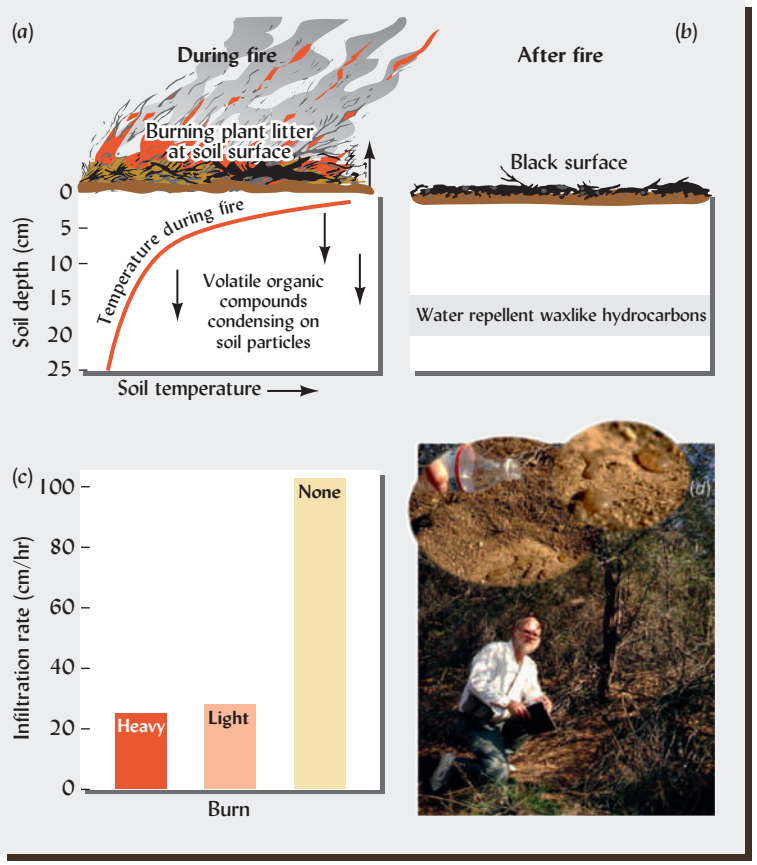

Figure 7.33 (a) *Wildfires heat up the surface layers of a sandy soil sufficiently to volatilize organic compounds from the soil organic matter and surface litter.* (b) *Some of the volatilized organics then diffuse away from the heat down into the soil and condense (solidify) on the surface of cooler soil particles. These condensed compounds are waxlike hydrocarbons that are water repellent and drastically reduce the infiltration of water into the soil for a period of years.* (d) *An ecologist investigates the soil under chaparral vegetation in southern California, USA, where dry season fires have created a water repellant layer a few cm below the surface. The inset photos show water beading up on this soil layer exposed by scrapping aside the upper 8 cm of loose, nonrepellent soil.* [Concepts from DeBano (2000), bar graph from data in Dryness (1976); photos courtesy of Ray R. Weil]

7.9 ABSORPTION AND LOSS OF SOLAR ENERGY[9]

The temperature of soils in the field is directly or indirectly dependent on at least three factors: (1) the net amount of heat energy the soil absorbs; (2) the heat energy required to bring about a given change in the temperature of a soil; and (3) the energy required for processes such as evaporation, which are constantly occurring at or near the surface of soils.

Solar radiation is the primary source of energy to heat soils. But clouds and dust particles intercept the sun's rays and absorb, scatter, or reflect most of the energy (Figure 7.34). Only about 35%–40% of the solar radiation actually reaches the Earth in cloudy humid regions and 75% in cloud-free arid areas. The global average is about 50%.

Little of the solar energy reaching the Earth actually results in soil warming. The energy is used primarily to evaporate water from the soil or leaf surfaces or is radiated or reflected back to the sky. Only about 10% is absorbed by and warms the soil. Even so, this warming is critical to soil processes and to plants growing in soils.

Albedo. The fraction of incident radiation that is reflected by the land surface is termed the **albedo** and ranges from as low as 0.1–0.2 for dark-colored, rough soil surfaces to as high as 0.5 or more for smooth, light-colored surfaces. Vegetation may affect the surface albedo either way, depending on whether it is dark green and growing or yellow and dormant.

The fact that dark-colored soils absorb more energy than lighter-colored ones does not necessarily imply, however, that dark soils are always warmer. In fact, the opposite is often true. In most landscapes, the darkest soils are those found in the low spots where excessive wetness has caused organic matter to accumulate. Therefore, the darkest soils are also usually

[9]For application of these principles to the role of soil moisture in models of global warming, see Lin et al. (2003).

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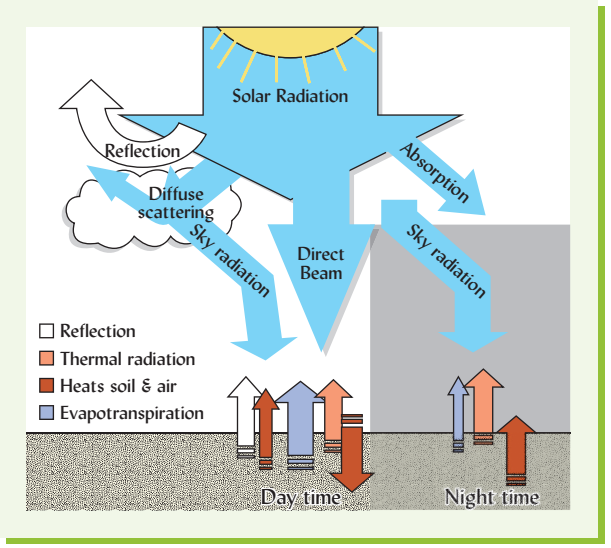

Figure 7.34 *Schematic representation of the radiation balance in daytime and nighttime in the spring or early summer in a temperate region. About half the solar radiation reaches the Earth, either directly or indirectly, from sky radiation. Most radiation energy that strikes the Earth in the daytime is used to drive evapotranspiration or is radiated back to the atmosphere. Only a small portion, perhaps 10%, actually heats the soil. At night the soil loses some heat, and some evaporation and thermal radiation occur.* (Diagram courtesy of Ray R. Weil)

the wettest. The water in these soils will absorb much energy with only little change in temperature (see Section 7.10), and it also cools the soil when it evaporates.

Slope Angle and Aspect. The angle at which the sun's rays strike the soil also influences soil temperature. If the incoming path of the rays of solar energy is perpendicular to the soil surface, energy absorption (and soil temperature increase) is greatest (Figure 7.35). The effect of the direction of slope, or **aspect**, on forest species is illustrated in the photo in Figure 7.35.

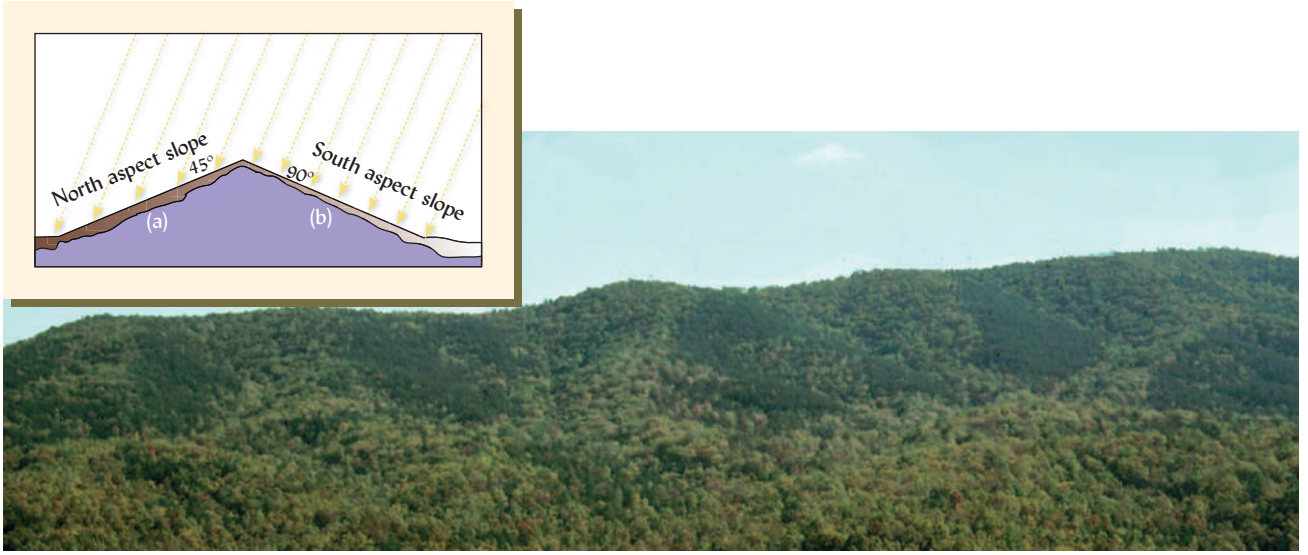

Figure 7.35 (Inset diagram) *Effect of slope aspect on solar radiation received per unit land area. Slope* (a) *is north facing and receives solar radiation at an angle of 45° to the ground surface so only 5 units of solar radiation (arrows) hit the unit of land area. The same land area on the south-facing slope* (b) *receives 7 units of radiation at a 90° angle to the ground. In other words, if a given amount of radiation from the sun strikes the soil at right angles, the radiation is concentrated in a relatively small area, and the soil warms quite rapidly. This is one of the reasons why north slopes tend to have cooler soils than south slopes. It also accounts for the colder soils in winter than in summer.* (Photo) *A view looking eastward toward a forested mountain in Virginia, USA, illustrates the temperature effect. The main ridge* (left to right) *runs north-south and the smaller side ridges run east-west (up and down). The dark patches are pine trees in this predominantly hardwood deciduous forest. The pines dominate the southern slopes on each east-west ridge. The soils on the southern slopes are warmer and therefore drier, less deeply weathered, and lower in organic matter.* (Photo and diagram courtesy of Ray R. Weil)

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Planting crops on soil ridges is one method of controlling the soil aspect on a microscale. This is most effectively done at high latitudes by planting crops on the south- or southwest-facing sides of ridges. The ridges need to be only about 25 cm tall to have a major effect. For example, in Fairbanks, Alaska, midafternoon soil temperatures (at 1 cm depth) in early May on the south side of such a ridge can be about 15 °C warmer than on the north side and about 8 °C warmer than on level ground.

Rain. Mention should also be made of the effect of rain or irrigation water on soil temperature. In the summer, rainfall cools the soil, since it is often cooler than the soil it penetrates. On the other hand, in temperate zones, spring rain definitely warms the surface soil in the short term as the relatively warm water moves into cold soil. However, spring rain, by increasing the amount of solar energy used in evaporating water from the soil, can also accentuate low temperatures.

Soil Cover. Whether the soil is bare or is covered with vegetation, mulch, or snow is another factor markedly influencing the amount of solar radiation reaching the soil. Bare soils warm up more quickly and cool off more rapidly than those covered with vegetation, with snow, or with plastic mulches. Frost penetration during the winter is considerably greater in bare, noninsulated land.

Even low-growing vegetation such as turfgrass has a very noticeable influence on soil temperature and on the temperature of the surroundings (Table 7.5). Much of the cooling effect is due to heat dissipated by transpiration of water. To experience this effect, on a blistering hot day, try having a picnic on an asphalt parking lot instead of on a growing green lawn!

The effect of a dense forest is universally recognized. Timber-harvest practices that leave sufficient canopy to provide about 50% shade will likely prevent undue soil warming that could hasten the loss of soil organic matter or the onset of anaerobic conditions in wet soils. The effect of timber harvest to soil temperature as deep as 50 cm is seen in the case presented in Table 7.6, where tree removal warmed the soil in spring, even though it also raised the soil water content, since trees were no longer taking up water. However, as we shall see in the next section, a higher water content normally slows the warming of soils in spring.

7.10 THERMAL PROPERTIES OF SOILS

Specific Heat of Soils

A dry soil is more easily heated than a wet one. This is because the amount of energy required to raise the temperature of water by 1 °C (its heat capacity) is much higher than that required to warm soil solids by 1 °C. When heat capacity is expressed per unit mass—for

Table 7.5
MAXIMUM SURFACE TEMPERATURES FOR FOUR TYPES OF SURFACES ON A SUNNY AUGUST DAY IN COLLEGE STATION IN TEXAS, USA

	Maximum temperature, °C	
Type of surface	Day	Night
Green, growing turfgrass	31	24
Dry, bare soil	39	26
Brown, summer-dormant grass	52	27
Dry synthetic sports turf	70	29

Data from Beard and Green (1994).

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Table 7.6
TREE REMOVAL EFFECT ON SOIL AERATION AND TEMPERATURE IN A SUBTROPICAL PINE FOREST
Removal of 55-year-old loblolly pine trees reduced transpiration and shading, resulting in a higher water table, warmer spring temperatures, and lower redox potentials in this Vertic Ochraqualf. Because warmer temperatures stimulated microbial activity, E_h was lower in spring, though the soil was wetter in winter.

		Soil temperature, °C		Soil redox potentials E_h, V	
Site treatment	Time soil is saturated, %	Winter	Spring	Winter	Spring
Measured at 50-cm depth					
Undisturbed pine stand	39	11.8	18.3	0.83	0.65
Trees cut, soil not compacted	71	11.7	20.5	0.51	0.11
Measured at 100-cm depth					
Undisturbed pine stand	57	13.3	17.3	0.83	0.49
Trees cut, soil not compacted	69	13.2	18.7	0.54	0.22

Data from Tiarks et al. (1996).

example, in calories per gram (cal/g)—it is called **specific heat** or heat capacity *c*. The specific heat of pure water is defined as 1.00 cal/g (or 4.18 joules per gram, J/g); that of dry soil is about 0.2 cal/g (0.8 J/g).

The specific heat largely controls the degree to which soils warm up in the spring, wetter soils warming more slowly than drier ones (see Box 7.4). Furthermore, if the water does not drain freely from the wet soil, it will be evaporated, a process that is very energy consuming, as the next section will show.

The high specific heat of soils is also used in the design of energy-efficient geothermic temperature control systems that both warm and cool buildings. To maximize heat-exchange contact with the soil, a network of pipes is laid underground near the building to be heated and cooled. Advantage is taken of the fact that subsoils are generally warmer than the atmosphere in the winter and cooler than the atmosphere in the summer. Fluid circulating through the network of pipes absorbs heat from the soil during the winter and releases it to the soil in the summer. The high specific heat of soils combined with their enormous mass permits a large exchange of energy to take place without greatly modifying the soil temperature.

Heat of Vaporization

The evaporation of water from soil surfaces requires a large amount of energy, 540 kilocalories (kcal) or 2.257 megajoules (mJ) for every kilogram of water vaporized. This use of energy for evaporation cools the soil, much the way it chills a person who comes out from the water after swimming on a windy day.

For example, if the amount of water associated with 100 g of dry soil was reduced by evaporation from 25 to 24 g (only about a 1% decrease) and if all the thermal energy needed to evaporate the water came from the moist soil, the soil would be cooled by about 12 °C. Such a figure is hypothetical because only a part of the heat of vaporization comes from the soil itself. Nevertheless, it indicates the tremendous cooling influence of evaporation.

The low temperature of a wet soil may be due partially to evaporation and partially to high specific heat. The temperature of the upper few centimeters of wet soil is commonly 3–6 °C lower than that of a drier soil. This is a significant factor in the spring in a temperate zone, when a few degrees will make the difference between the germination or lack of germination of seeds, or the microbial release or lack of release of nutrients from organic matter.

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BOX 7.4

CALCULATING THE SPECIFIC HEAT (HEAT CAPACITY) OF MOIST SOILS

Soil water content markedly impacts soil temperature changes through its effect on the specific heat or heat capacity c of a soil. For example, consider two soils with comparable characteristics, soil A, a relatively dry soil with 10 g water/100 g soil solids, and soil B, a wetter soil with 30 g water/100 g soil solids.

We can assume the following values for specific heat:

$$\text{Water} = 1.0\ \text{cal/g and dry mineral soil} = 0.2\ \text{cal/g}$$

For soil A with 10 g water/100 g dry soil, or 0.1 g water/g dry soil, the number of calories required to raise the temperature of 0.1 g of water by 1 °C is: $0.1\ \text{g} \times 1.0\ \text{cal/g} = 0.1\ \text{cal}$. The corresponding figure for the 1.0 g of soil solids is:

$$1\ \text{g} \times 0.2\ \text{cal/g} = 0.2\ \text{cal}.$$

Thus, a total of 0.3 cal (0.1 + 0.2) is required to raise the temperature of 1.1 g (1.0 + 0.1) of the moist soil by 1 °C. Since the specific heat is the number of calories required to raise the temperature of 1 g of moist soil by 1 °C, we can calculate the specific heat of soil A as follows:

$$c_{\text{soil A}} = \frac{0.3}{1.1} = 0.273\ \text{cal/g}$$

These calculations can be expressed as a simple equation to calculate the weighted average specific heat of a mixture of substances:

$$c_{\text{moist soil}} = \frac{c_1 m_1 + c_2 m_2}{m_1 + m_2} \tag{7.7}$$

where c_1 and m_1 are the specific heat and mass of substance 1 (the dry mineral soil, in this case), and c_2 and m_2 are the specific heat of substance 2 (the water, in this case).

Applying this equation to soil A, we again calculate that $c_{\text{soil A}}$ is 0.273 cal/g, as follows:

$$c_{\text{soil A}} = \frac{0.2\ \text{cal/g} \times 1.0\ \text{g} + 1.0\ \text{cal/g} \times 0.10\ \text{g}}{1.0\ \text{g} + 0.10\ \text{g}}$$

$$= \frac{0.30\ \text{cal}}{1.1\ \text{g}} = 0.273\ \text{cal/g}$$

In the same manner, we calculate the specific heat of the wetter soil B:

$$c_{\text{soil B}} = \frac{0.2\ \text{cal/g} \times 1.0\ \text{g} + 1.0\ \text{cal/g} \times 0.30\ \text{g}}{1.0\ \text{g} + 0.30\ \text{g}}$$

$$= \frac{0.50\ \text{cal}}{1.3\ \text{g}} = 0.385\ \text{cal/g}$$

The wetter soil B has a specific heat c_B of 0.385 cal/g, whereas the drier soil A has a specific heat c_A of 0.273 cal/g. Because it must absorb an additional 0.112 cal (0.385−0.273) of solar radiation for every degree of temperature rise, the wetter soil will warm up much more slowly than the drier soil.

Thermal Conductivity of Soils

As shown in Section 7.9, some of the solar radiation that reaches the Earth slowly penetrates the profile largely by conduction; this is the same process by which heat moves to the handle of a cast-iron frying pan. The movement of heat in soil is analogous to the movement of water (see Section 5.5), the rate of flow being determined by a driving force and by the ease with which heat flows through the soil. This can be expressed as Fourier's law:

$$Q_h = \lambda \times \frac{\Delta T}{x} \tag{7.8}$$

where Q_h is the *thermal flux*, the quantity of heat transferred across a unit cross-sectional area in a unit time; λ is the **thermal conductivity** of the soil; and $\Delta T/x$ is the temperature gradient over distance x that serves as the driving force for the conduction of heat.

The thermal conductivity λ of soil is influenced by a number of factors, the most important being the moisture content of the soil and the degree of compaction (see Figure 7.36). Heat passes through water many times faster than through air. As the water content increases in a soil, the air content decreases, and the transfer resistance is decidedly lowered. When sufficient water is present to form a bridge between most of the soil particles, further additions will have little effect on heat conduction. Heat moves through mineral particles even faster than through water, so when particle-to-particle contact is increased by soil compaction, heat-transfer rates are also increased. Therefore, a wet, compacted soil would be the poorest insulator or the best conductor of heat. Here again the interconnectedness of soil properties is demonstrated.

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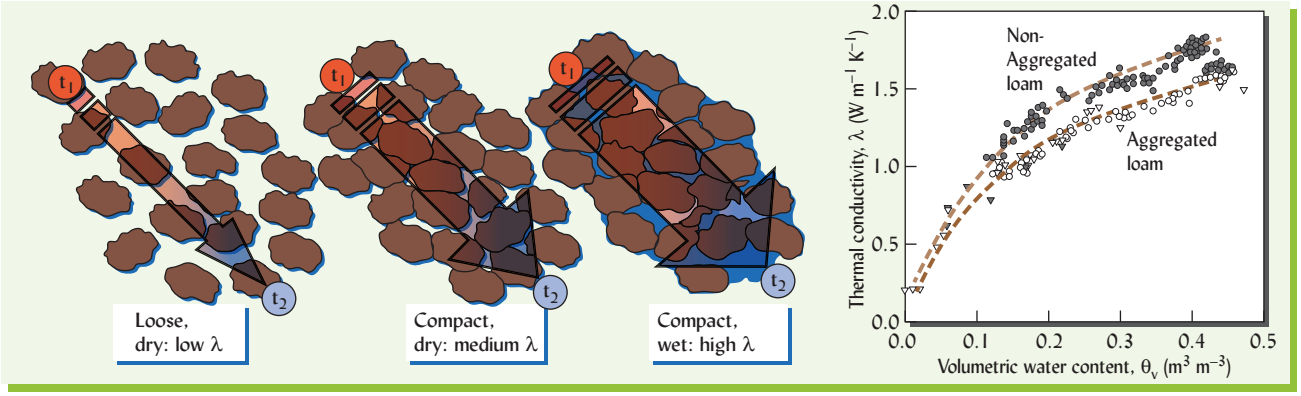

Figure 7.36 *Bulk density and water content affect the rate at which heat is transferred through soils from a warm zone (X1) to a cooler zone (X2). The arrows represent heat transfer through the soil, the rate of transfer being in proportion to the soil thermal conductivity λ represented by the arrow thickness. Higher bulk density from soil compaction increases particle-to-particle contact, which in turn hastens heat transfer because the thermal conductivity of mineral particles is much higher than that of air. If the remaining gaps between particles become filled with water instead of air, the soil thermal conductivity increases still more because water also conducts heat better than air. Therefore wet, compacted soils transfer heat most rapidly. The graph at right shows measurements of thermal conductivity as affected by soil aggregation and increasing water content for a loam soil. Lack of aggregation has a similar effect to compaction.* [Diagram courtesy of Ray R. Weil, graph modified from Ju et al. (2011)]

Relatively dry soil makes a good insulating material. Buildings built mostly underground can take advantage of both the low thermal conductivity and relatively high heat capacity of large volumes of soil (see Figure 7.37).

Because of relatively low thermal conductivities, changes in subsoil temperature lag behind those of the surface layers. Moreover, temperature changes are of a smaller magnitude in the subsoil. In temperate regions, surface soils in general are expected to be warmer in summer and cooler in winter than the subsoil, especially the lower horizons of the subsoil. Soil thermal conductivity can also affect air temperature above the soil, as shown in Figure 7.38.

Variation with Time and Depth

Soil temperature at any time and place depends on the ratio of the energy absorbed to that being lost. The constant change in this relationship is reflected in seasonal, monthly, and daily temperature fluctuations. Figure 7.39 illustrates the considerable seasonal variations of soil temperature that occur in northern hemisphere temperate regions.

In the subsoil, the seasonal temperature increases and decreases lag behind changes registered in the surface soil and in the air. Accordingly, Figure 7.39 shows surface soil temperatures in March responding to the warming of spring, while temperatures of the subsoil still reflect the cold of winter. Subsoil temperatures are less variable than air and

Figure 7.37 *This high school in Oklahoma, USA, has been built into the ground with only one side exposed. This design takes advantage of the high specific heat and low thermal conductivity of the overlying soils, keeping the school warm in winter and cool in summer with a minimum of energy used for heating or air-conditioning.* (Photo courtesy of Ray R. Weil)

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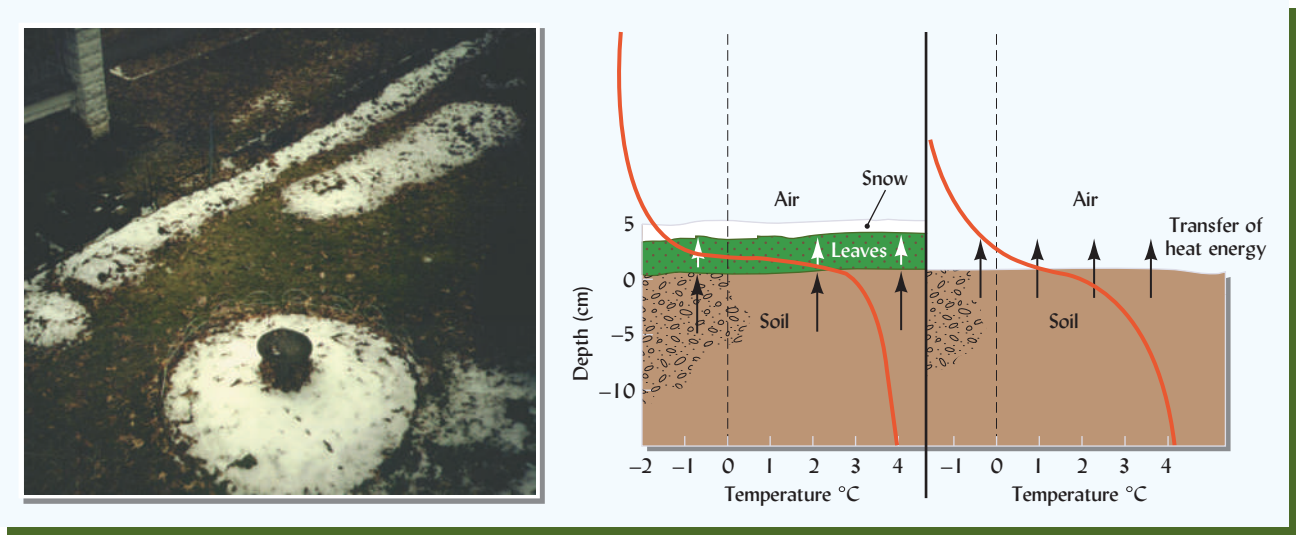
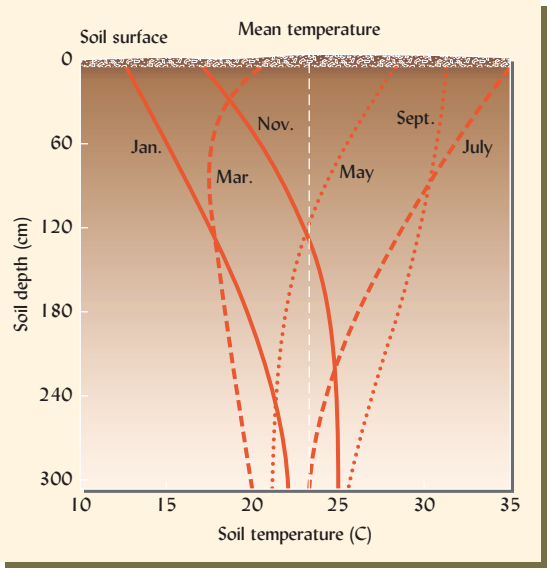


Figure 7.38 *Transfer of heat energy from soil to air. The scene, looking down on a garden after an early fall snowstorm, shows snow on the leaf-mulched flower beds, but not on areas where the soil is bare or covered with thin turf. The reason for this uneven accumulation of snow can be seen in the temperature profiles. Having stored heat from the sun, the soil layers are often warmer than the air as temperatures drop in fall (this is also true at night during other seasons). On bare soil, heat energy is transferred rapidly from the deeper layers to the surface, the rate of transfer being enhanced by high moisture content or compaction, which increases the thermal conductivity of the soil. As a result, the soil surface and the air above it are warmed to above freezing, so snow melts and does not accumulate. The leaf mulch, which has a low thermal conductivity, acts as an insulating blanket that slows the transfer of stored heat energy from the soil to the air. The upper surface of the mulch is therefore hardly warmed by the soil, and the snow remains frozen and accumulates. A heavy covering of snow can itself act as an insulating blanket.* (Photo and diagram courtesy of Ray R. Weil)

surface soil temperatures, although there is some temperature fluctuation even at 300 cm deep (Figure 7.39).

Compared to the surface soil and the air, deep soil layers are generally warmer in the late fall and winter and cooler in the spring and summer. On a daily basis (see Figure 7.40), soil reaches its maximum temperature later in the afternoon or evening than does the air, the lag time being greater and the fluctuation less pronounced for greater depths. Deeper than 4–5 m, the temperature changes little and approximates the mean annual air temperature (a fact experienced by people visiting deep caverns).

Figure 7.39 *Average monthly soil temperatures for 6 of the 12 months of the year at different soil depths at College Station in Texas, USA (1951–1955). Note the lag in soil temperature change at the lower depths.* [Graph based on data selected from Fluker (1958)]



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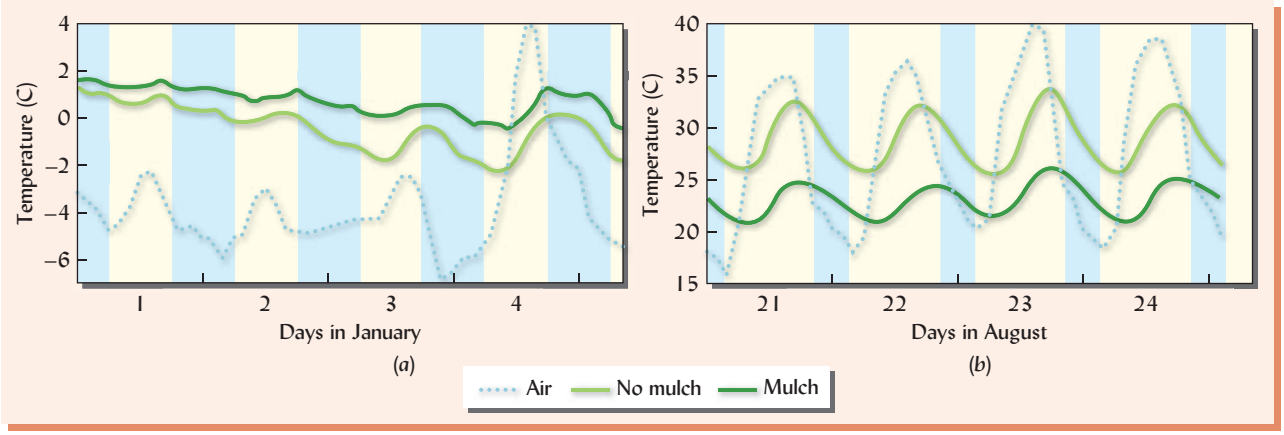

Figure 7.40 (Right) *Influence of straw mulch (8 tons/ha) on air temperature at a depth of 10 cm during an August hot spell in Bushland in Texas, USA. Note that the soil temperatures in the mulched area are consistently lower than where no mulch was applied.* (Left) *During a cold period in January, the soil temperature was higher in the mulched than in the unmulched area. The shaded bars represent nighttime. Note that air temperatures fluctuate much more widely than do soil temperatures and that peak soil temperature is reached several hours after the air temperature peaks.* [Redrawn from Unger (1978); used with permission of American Society of Agronomy]

7.11 SOIL TEMPERATURE CONTROL

The temperature of field soils is usually not subject to radical human regulation. However, two kinds of management practice have significant effects on soil temperature: those that affect the vegetative or mulch covering the soil surface and those that affect soil moisture. These effects have meaningful biological implications.

Organic Mulches and Plant-Residue Management

Figure 7.40 shows that mulches effectively buffer extremes in soil temperatures. In periods of hot weather, they keep the surface soil cooler than where no cover is present; in contrast, during cold weather they keep the soil warmer than it would be if bare.

The forest floor is a prime example of a natural temperature-modifying mulch. It is not surprising, therefore, that timber harvest practices can markedly affect forest soil temperature regimes (Figure 7.41 and Table 7.6). Disturbance of the leaf mulch, changes in water content due to reduced evapotranspiration, and compaction by machinery are all factors that influence soil temperatures through thermal conductivity. Reduced shading after tree removal also lets in more solar radiation.

Mulch from Conservation Tillage. Until fairly recently, the labor and expense of carrying and spreading mulch materials limited their use in modifying soil temperature extremes mostly to home gardens and flower beds. Although these uses are still important, the use of mulches has been extended to field-crop culture in areas that have adopted conservation tillage practices. Conservation tillage leaves most or all of the residues from crops and cover crops at or near the soil surface. Thereby, the conservation farmer grows mulch in place, rather than transporting it to the field.

Concerns in Cool Climates. In no-tillage systems all residues are left on the surface as a mulch. While mulch provides great control over erosion (see Section 17.6), it also causes the soil to warm more slowly during spring than where the soil is left bare. In cold climates the soil-temperature-depressing effects of mulch may require delayed planting and can have serious negative impacts on crop productivity. The lower soil temperatures in spring resulting from mulch practices inhibit seed germination, seedling performance, and, often, the yields of such warm season crops as corn or soybean. The effect of the residue mulch is most

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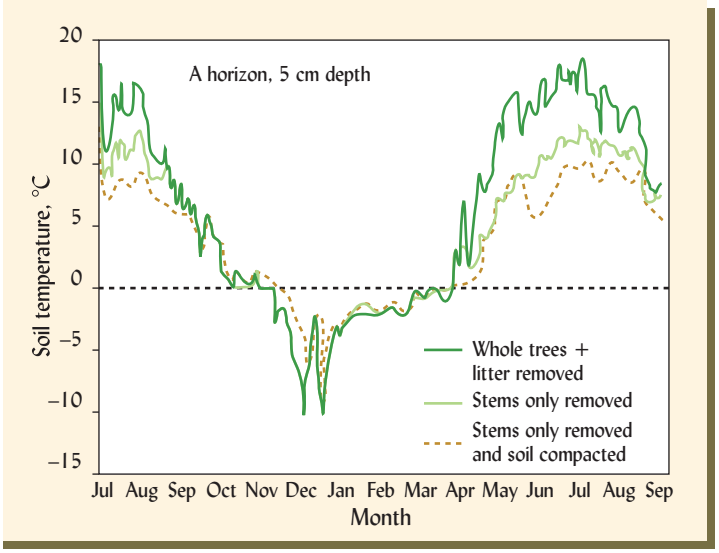

Figure 7.41 *Soil temperature in an aspen-spruce boreal forest after two levels of harvest and soil compaction. One harvest procedure removed only the stems (tree trunks) with branches and foliage left on the soil, while a second procedure removed whole trees and stripped woody materials and litter to expose the mineral soil (this was done to simulate the kind of damage often inflicted by poorly managed harvest equipment). The soils were either left undisturbed during harvest, or they were severely compacted. The compacted treatment is shown only for the whole-tree removal procedure as compaction did not affect soil temperature where harvest removed only tree trunks. Exposure of the mineral soil A horizon resulted in much warmer temperatures in summer and somewhat colder soil in winter. Compaction of this soil mainly slowed warming in summer, partly because of a higher water content (and therefore a higher heat capacity). The Aquepts (Luvic Gleysols in the Canadian soil classification) at this site in British Columbia included about 20–30 cm of silt loam material over a clay loam.* [From Tan et al. (2005)]

pronounced in lowering the midday maximum temperature and has much less effect on the minimum temperature reached at night (Figure 7.42). The addition of row cleaners to the no-tillage planter can alleviate this problem by pushing aside the residues in just a 10-cm-wide band from over the seed row (this modified no-till system is referred to as MNT in Figure 7.42). Another approach to solving this problem is to ridge the soil, permit water to drain out of the ridge, and then plant on the drier, warmer ridgetop (or on the south side of the ridge—see Section 7.9).

Advantages in Warm Climates. In warm regions, delayed planting is not a problem. In fact, the cooler near-surface soil temperatures under a mulch may reduce heat stress on roots during summer. Plant-residue mulches also conserve soil moisture by decreasing evaporation. The resulting cooler, moist surface layer of soil is an important part of no-tillage systems because it allows roots to proliferate in this zone, where nutrient and aeration conditions are optimal.

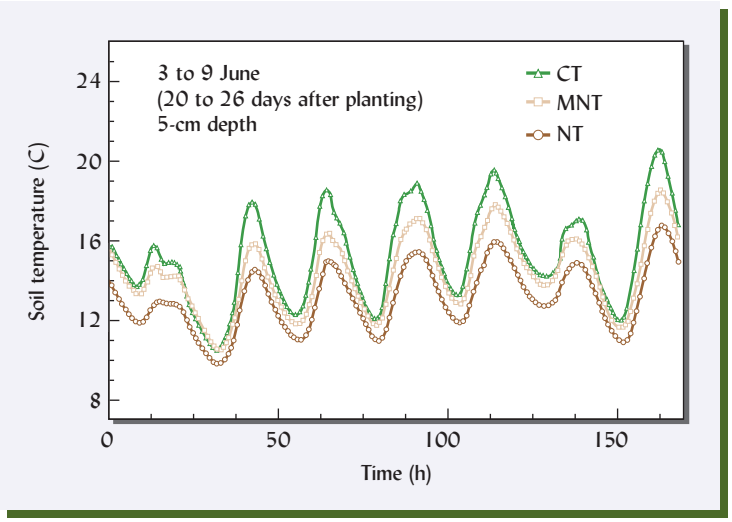

Figure 7.42 *Tillage effects on hourly temperature changes near the surface of a cold Alfisol in northern British Columbia, Canada. The soil had been managed to grow barley under no-tillage (NT) and conventional (clean surface without residues) tillage (CT) systems for the previous 14 years. In the clean-tilled soil, midafternoon temperatures peaked at 4 °C higher than those in the residue mulch–covered no-tillage soil. A modification of the no-tillage system (MNT) that pushed aside the residues in a narrow (7.5-cm wide) band from over the seeding row eliminated much of the temperature depression while keeping most of the surface covered by the soil- and water-conserving mulch. Note the daily temperature changes and the general warming trend during the seven days shown.* [From Arshad and Azooz (1996)]

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Plastic Mulches

One of the reasons for the popularity of plastic mulches for gardens and high-value specialty crops is their effect on soil temperature (see Section 6.4 for their effect on soil moisture). In contrast to the cooling effects of organic mulches just discussed, plastic mulches generally increase soil temperature. Clear plastic has a greater heating effect than black plastic. In temperate regions, this effect can be used to extend the growing season or to hasten production to take advantage of the higher prices offered by early-season markets. Figure 7.43 shows the use of clear plastic mulch for winter-grown strawberries in Southern California.

Major disadvantages of both clear and black plastic mulch are the nonrenewable fossil fuels used in their manufacture, the difficulty of removing the material from the field at the end of the season, and the problem of properly disposing of all that soil-encrusted, shredded plastic waste. One solution may be found in newer biodegradable plastic films that have been manufactured from such natural renewable raw materials as corn starch. Figure 7.44 illustrates the use of biodegradable plastic film on a residue-covered soil in order to allow earlier than normal planting of a sweet corn crop in a cool climate.

In warmer climates, and during the summer months, the soil-heating effect of plastic mulches may be quite detrimental, inhibiting root growth in the upper soil layers and sometimes seriously decreasing crop yields. Table 7.7 provides an example in which the benefits of weed control and moisture conservation by plastic mulch were outweighed by the detrimental effects of excessive soil heating.

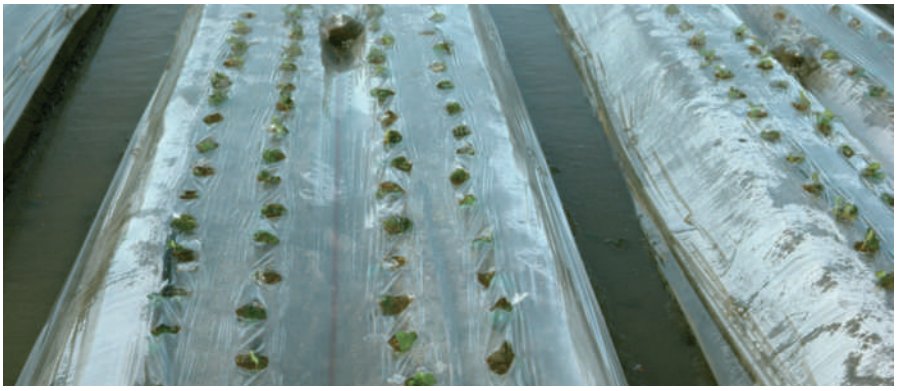

Figure 7.43 *These winter-grown Southern California strawberries will come to market when prices are still high because of the effect of the clear plastic mulch on soil temperature.* (Photo courtesy of Ray R. Weil)

Figure 7.44 *Laying down a special biodegradable clear plastic mulch to hasten soil warming for a no-till sweet corn crop on hilly cropland in Pennsylvania, USA. The farmer's no-till system keeps the soil covered with plant residues that prevent erosion but also slow soil warming in spring. Each strip of plastic mulch covers two rows of corn seeds that have already been planted with a no-till planter. The plastic film acts like a greenhouse to trap solar energy, warm the soil, and hasten the corn germination and early growth. When the corn seedlings are about 20 cm tall the farmer will slit the plastic film, allowing the plants to grow unimpeded. By the time the corn canopy has closed, the plastic will have largely disappeared, having served its function of getting the corn off to an early start.* (Photo courtesy of Ray R. Weil)

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Table 7.7
SOIL TEMPERATURE AND TOMATO YIELD WITH STRAW OR BLACK PLASTIC MULCH[a]
Means for two years of tomato production on a sandy Ultisol in Georgia, USA. Straw kept surface soil below detrimental temperatures, while increasing rainwater infiltration and reducing compaction. Daily drip irrigation could not overcome the temperature effects of black plastic mulch.

	Not irrigated		Irrigated daily	
	Straw mulch	Plastic mulch	Straw mulch	Plastic mulch
Average soil temperature, °C	24	37	24	35
Tomato yield, Mg/ha	68	30	70	24

[a]Soil temperature measured at 5 cm below the soil surface, average of weeks 2–10 of the growing season.
Data calculated from Tindall et al. (1991).

Moisture Control

Another means of exercising some control over soil temperature is by controlling soil moisture. Poorly drained soils in temperate regions that are wet in the spring have temperatures 3–6 °C lower than comparable well-drained soils. By removing excess water warmer soils can be achieved. Water can be removed by installing drainage systems using ditches and underground pipes (see Section 6.7). An alternative to artificial drainage is the construction of raised beds or the ridging systems of tillage just referred.

As is the case with soil air, the controlling influence of soil water on soil temperature is apparent everywhere. Whether a problem concerns capture of solar energy, loss of energy to the atmosphere, or the movement of heat within the soil, the amount of water present is always important. Water regulation seems to be a key to what little practical temperature control is possible for soils in the field.

7.12 CONCLUSION

Soil aeration and soil temperature critically affect the quality of soils as habitats for plants and other organisms. Most plants have definite requirements for soil oxygen along with limited tolerance for carbon dioxide, methane, and other such gases found in poorly aerated soils. Some microbes, such as the nitrifiers and general-purpose decay organisms, are also constrained by low levels of soil oxygen. Through its effect on soil redox potential (E_h) and acidity (pH), soil aeration status helps determine the forms present, availability, mobility, and possible toxicity of such elements as nitrogen, sulfur, carbon, iron, manganese, chromium, and many others.

Soils with extremely wet moisture regimes are unique with respect to their morphology and chemistry and support unique plant communities. Such hydric soils are characteristic of wetlands and help these ecosystems perform a myriad of valuable ecosystem functions.

Plants as well as microbes are also quite sensitive to differences in soil temperature, particularly in temperate climates where low temperatures can limit essential biological processes. Soil temperature also impacts the use of soils for engineering purposes, again primarily in the cooler climates. Frost action, which can move perennial plants such as alfalfa out of the ground, can also cause damage to building foundations, fence posts, sidewalks, and highways.

Soil water exerts a major influence over both soil aeration and soil temperature. It competes with soil air for the occupancy of soil pores and interferes with the diffusion of gases into and out of the soil. Soil water also resists changes in soil temperature by virtue of its high specific heat and its high energy requirement for evaporation. Fire, mulching, and drainage are other factors that markedly influence soil temperatures.

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STUDY QUESTIONS

1. What are the two principal gases involved with soil aeration, and how do their relative amounts change as one samples deeper into a soil profile?
2. What is aerenchyma tissue, and how does it affect plant–soil relationships?
3. If the redox potential for a soil at pH 6 is near zero, write two reactions that you would expect to take place. How would the presence of a great deal of nitrate compounds affect the occurrence of these reactions?
4. It is sometimes said that organisms in anaerobic environments will use the combined oxygen in nitrate or sulfate instead of the oxygen in O_2. Why is this statement incorrect? What actually happens when organisms reduce sulfate or nitrate?
5. If an alluvial forest soil were flooded for 10 days and you sampled the gases evolving from the wet soil, what gases would you expect to find (other than oxygen and carbon dioxide)? In what order of appearance? Explain.
6. Explain why warm weather during periods of saturation is required in order to form a hydric soil.
7. If you were in the field trying to delineate the so-called drier end of a wetland area, what are three soil properties and three other indicators that you might look for?
8. For each of these gases, write a sentence to explain its relationship to wetland conditions: *ethylene, methane, nitrous oxide, oxygen,* and *hydrogen sulfide.*
9. What are the three major components that define a wetland?
10. Discuss four plant processes that are influenced by soil temperature.
11. Explain how a brush fire might lead to subsequent mudslides, as often occurs in California.
12. If you were to build a house below ground in order to save heating and cooling costs, would you firmly compact the soil around the house? Explain your answer.
13. If you measured a daily maximum air temperature of 28 °C at 1 P.M., what might you expect the daily maximum temperature to be at a 15-cm depth in the soil? At about what time of day would the maximum temperature occur at this depth? Explain.
14. In relation to soil temperature, explain why conservation tillage has been more popular in Missouri than in Minnesota.

REFERENCES

Arshad, A., and R. H. Azooz. 1996. "Tillage effects on soil thermal properties in a semiarid cold region." *Soil Science Society of America Journal* **60**:561–567.

Bailey-Serres, J., T. Fukao, D. J. Gibbs, M. J. Holdsworth, S. C. Lee, F. Licausi, P. Perata, L. A. C. J. Voesenek, and J. T. van Dongen. 2012. "Making sense of low oxygen sensing." *Trends in Plant Science* **17**:129–138.

Bartlett, R. J., and B. R. James. 1993. "Redox chemistry of soils." *Advances in Agronomy* **50**:151–208.

Bartlett, R. J., and D. S. Ross. 2005. "Chemistry of redox process in soils." In A. Tabatabai and D. Sparks (eds.). *Chemical Processes in Soils*. SSSA Book Series No. 8. Soil Science Society of America, Madison, WI, pp. 461–487.

Beard, J. B., and R. L. Green. 1994. "The role of turfgrasses in environmental protection and their benefits to humans," *Journal of Environmental Quality* **23**:452–460.

Buyanovsky, G. A., and G. H. Wagner. 1983. "Annual cycles of carbon dioxide level in soil air." *Soil Science Society of America Journal* **47**:1139–1145.

CAST. 1994. *Wetland Policy Issues*. Publication No. CC1994-1. Council for Agricultural Science and Technology, Ames, IA.

Costanza, R., R. D'arge, R. De Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. Van Den Belt. 1997. "The value of the world's ecosystem services and natural capital." *Nature* **387**:253–260.

Davidson, E. A., and S. E. Trumbore. 1995. "Gas diffusivity and production of CO_2 in deep soils of the eastern Amazon." *Tellus* **47B**:550–565.

DeBano, L. F. 2000. "The role of fire and soil heating on water repellency in wildland environments: A review." *Journal of Hydrology* **231/232**:195–206.

Drew, M. C. 1990. "Sensing soil oxygen." *Plant, Cell and Environment* **13**:681–693.

Dryness, C. T. 1976. "Effects of wildfire on soil wetability in the high cascades of Oregon," USDA Forest Service Research Paper PNW-202. USDA, Washington, DC.

Eilperin, J. 2005. "Developers sentenced in wetlands case," p. A-14, *The Washington Post*, December 07, 2005, Washington, DC.

Eswaren, H., P. Reich, P. Zdruli, and T. Levermann. 1996. "Global distribution of wetlands." *American Society of Agronomy Abstracts* 328.

Fluker, B. J. 1958. "Soil temperature." *Soil Science* 86:35–46.

Hurt, G. W., P. M. Whited, and R. F. Pringle (eds.). 1996. *Field Indicators of Hydric Soils in the United States*. USDA Natural Resources Conservation Service, Fort Worth, TX.

Husson, O. 2012. "Redox potential (E_h) and pH as drivers of soil/plant/microorganism systems: A transdisciplinary overview pointing to integrative opportunities for agronomy." *Plant and Soil* XX:1–29.

FOR REFERENCE PURPOSES ONLY

Ju, Z., T. Ren, and C. Hu. 2011. "Soil thermal conductivity as influenced by aggregation at intermediate water contents." *Soil Science Society of America Journal* **75**:26–29.

Lin, X., J. E. Smerdon, A. W. England, and H. N. Pollack. 2003. "A model study of the effects of climatic precipitation changes on ground temperatures." *Journal of Geophysics Research* **108**(D7):4230, doi:10.1029/2002JD002878.

Losi, M. E., C. Amrheim, and W. T. Frankenberger, Jr. 1994. "Bioremediation of chromatic contaminated groundwater by reduction and precipitation in surface soils." *Journal of Environmental Quality* **23**:1141–1150.

MacDonald, N. W., D. R. Zac, and K. S. Pregitzer. 1995. "Temperature effects on kinetics of microbial respiration and net nitrogen and sulfur mineralization." *Soil Science Society of America Journal* **59**:233–240.

McBride, M. B. 1994. *Environmental Chemistry of Soils*. Oxford University Press, New York.

Melillo, J. M., S. Butler, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, F. Bowles, R. Smith, L. Scott, C. Vario, T. Hill, A. Burton, Y.-M. Zhou, and J. Tang. 2011. "Soil warming, carbon-nitrogen interactions, and forest carbon budgets." *Proceedings of the National Academy of Sciences* **108**:9508–9512.

Molins, S., K.U. Mayer, C. Scheutz, and P. Kjeldsen. 2008. Transport and reaction processes affecting the attenuation of landfill gas in cover soils. J. Environ. Qual. **37**:459–468.

Patrick, W. H., Jr. 1977. "Oxygen content of soil air by a field method." *Soil Science Society of America Journal* **41**:651–652.

Patrick, W. H., Jr., and A. Jugsujinda. 1992. "Sequential reduction and oxidation of inorganic nitrogen, manganese, and iron in flooded soil." *Soil Science Society of America Journal* **56**:1071–1073.

Richardson, J. L., and M. J. Vepraskas. 2001. *Wetland Soils—Genesis, Hydrology, Landscapes, and Classification*. Lewis, Boca Raton, FL.

Sexstone, A. J., N. P. Revsbech, T. B. Parkin, and J. M. Tiedje. 1985. "Direct measurement of oxygen profiles and denitrification rates in soil aggregates." *Soil Science Society of America Journal* **49**:645–651.

Tan, X., S. X. Chang, and R. Kabzems. 2005. "Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study." *Forest Ecology and Management* **217**:158–170.

Tiarks, A. E., W. H. Hudnall, J. F. Ragus, and W. B. Patterson. 1996. "Effect of pine plantation harvesting and soil compaction on soil water and temperature regimes in a semi-tropical environment." In A. Schulte and D. Ruhiyat (eds.). *Proceedings of International Congress on Soils of Tropical Forest Ecosystems 3rd Conference on Forest Soils: Vol. 3, Soil and Water Relationships*. Mulawarmon University Press, Samarinda, Indonesia.

Tindall, J. A., R. B. Beverly, and D. E. Radcliff. 1991. "Mulch effect on soil properties and tomato growth using micro-irrigation." *Agronomy Journal* **83**:1028–1034.

Torrance, J. K., and F. J. Schellekens. 2006. "Chemical factors in soil freezing and frost heave." *Polar Record* **42**:33–42.

Unger, P. W. 1978. "Straw mulch effects on soil temperatures and sorghum germination and growth." *Agronomy Journal* **70**:858–864.

Vasilas, L. M., G. W. Hurt, and C. V. Noble. 2010. "Field indicators of hydric soils in the United States," version 7.0. United States Department of Agriculture, Natural Resources Conservation Service. ftp://ftp-fc.sc.egov.usda.gov/NSSC/Hydric_Soils/FieldIndicators_v7.pdf

Veneman, P. L. M., D. L. Lindbo, and L. A. Spokas. 1999. "Soil moisture and redoximorphic features: A historical perspective." In M. J. Rabenhorst, J. C. Bell, and P. A. McDaniel (eds.). *Quantifying Soil Hydromorphology*. Special Publication No. 54. Soil Science Society of America, Madison, WI.

Welsh, D., D. Smart, J. Boyer, P. Minkin, H. Smith, and T. McCandless (eds.). 1995. *Forested Wetlands: Functions, Benefits, and Use of Best Management Practices.* USDA Forest Service, Radnor, PA.

Wuethrich, B. 2000. "When permafrost isn't." *Smithsonian*, Comments and Notes, February 2000.

Xu, Q., and B. Huang. 2000. "Growth and physiological responses of creeping bentgrass to changes in air and soil temperatures." *Crop Science* **40**:1363–1368.

Yu, K., and W. H. Patrick, Jr. 2004. "Redox window with minimum global warming potential contribution from rice soils." *Soil Science Society of America Journal* **68**: 2086–2091.

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Tillage and erosion expose a red clay soil landscape. (Ray R. Weil)

8 The Colloidal Fraction: Seat of Soil Chemical and Physical Activity

Not even the … clay can keep a secret if memory is stronger than time.
—*Rick Bragg in* Somebody Told Me

Why is it more difficult to restore productivity after logging a tropical rain forest on Oxisols than a temperate forest on Alfisols? Why do utility poles lean every which way across landscapes of black clay soils? How can using sewage effluent for irrigation contribute to the safe recharge of groundwater aquifers? Why would a nuclear power plant accident seriously contaminate food grown on some downwind soils, but not on others? The answers to these and other environmental mysteries lie in the nature of the smallest of soil particles, the clay and humus **colloids**. These particles are not just extra-small fragments of rock and organic matter. They are highly reactive materials with electrically charged surfaces. Because of their size and shape, they give the soil an enormous amount of reactive **surface area**. It is the colloids, then, that allow the soil to serve as nature's great electrostatic chemical reactor.

Each tiny colloid particle carries a swarm of positively and negatively charged ions (cations and anions) that is attracted to electrostatic charges on its surface. The ions are held tightly enough by the **soil colloids** to greatly reduce their loss in drainage waters, but loosely enough to allow plant roots access to the nutrients among them. Other modes of adsorption bind ions more tightly so that they are no longer available for plant uptake, reaction with the soil solution, or leaching loss to the environment. In addition to plant nutrient ions, soil colloids also bind with water molecules, biomolecules (e.g., DNA, hormones, or antibiotics), viruses, toxic metals, pesticides, and a host of other mineral and organic substances in the environment. Hence, soil colloids greatly impact nearly all ecosystem functions.

We shall see that different soils are endowed with different types of clays that, along with humus, elicit very different types of physical and chemical behaviors. Certain clay minerals are much more reactive than others. Some are more dramatically influenced than others by the acidity of the soil and other environmental factors. Studying the soil colloids in some detail will deepen your understanding of soil architecture (Chapter 4) and soil water (Chapters 5 and 6). Knowledge of the structure, origin, and behavior of the different types of soil colloids will also help you understand soil chemical and biological processes (Chapters 9–15) so you can make better decisions regarding the use of soil resources.

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8.1 GENERAL PROPERTIES AND TYPES OF SOIL COLLOIDS

Size

The clay and humus particles in soils are referred to collectively as the **colloidal fraction** because of their extremely small size and colloid-like behavior. So small, they are visible only with an electron microscope. Particles behave as colloids if they are less than about 1 μm (0.000001 m) in diameter, although some soil scientists consider 2 μm to mark the upper boundary of the colloidal fraction to coincide with the definition of the clay particle size fraction.

Surface Area

As discussed in Section 4.2, the smaller the size of the particles in a given mass of soil, the greater the surface area exposed for adsorption, catalysis, precipitation, microbial colonization, and other surface phenomena. Because of their small size, all soil colloids expose a large **external surface** area per unit mass, more than 1000 times the surface area of the same mass of sand particles. Some silicate clays also possess extensive **internal surface** area between the layers of their plate-like crystal units. To grasp the relative magnitude of the internal surface area, remember that these clays are structured much like this book. If you were to paint the external surfaces of this book (the covers and edges), a single brush of paint would do. However, to cover the internal surfaces (both sides of each page in the book) you would need a very large amount of paint.

The total surface area of soil colloids ranges from 10 m^2/g for clays with only external surfaces, to more than 800 m^2/g for clays with extensive internal surfaces. To put this in perspective, we can calculate that the surface area exposed within 1 ha (about the size of a football field) of a 1.5-m-deep fine-textured soil (45% clay) might be as great as 8,700,000 km^2 (the land area of the entire United States).

Surface Charges

The internal and external surfaces of soil colloids carry positive and/or negative electrostatic charges. For most soil colloids, electronegative charges predominate, although some mineral colloids in very acid soils have a net electropositive charge. As we shall see in Sections 8.3 to 8.7, the amount and origin of surface charge differs greatly among the different types of soil colloids and, in some cases, is influenced by changes in chemical conditions, such as soil pH. The charges on the colloid surfaces attract or repulse substances in the soil solution as well as neighboring colloid particles. These reactions, in turn, greatly influence soil chemical and physical behavior.

Adsorption of Cations and Anions

Of particular significance is the attraction of positively charged ions (**cations**) to the surfaces of negatively charged soil colloids. Each colloid particle attracts thousands of Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, H^+, and Na^+ ions and lesser numbers of other cations. In moist soils the cations exist in the hydrated state (surrounded by a shell of water molecules), but for simplicity in this text, we will show just the cations (e.g., Ca^{2+} or H^+) rather than the hydrated forms (e.g., $Ca(H_2O)_6^{2+}$ or the hydronium ion, H_3O^+). These hydrated cations constantly vibrate about in a swarm near the colloid surface, held there by electrostatic attraction to the colloid's negative charges. Frequently, an individual cation will break away from the swarm and move out to the soil solution. When this happens, another cation of equal charge will simultaneously move in from the soil solution and take its place. This process, termed **cation exchange**, will be discussed in detail (Section 8.8) because of its fundamental importance in nutrient cycling and other environmental processes. The cations swarming about near the colloidal surface are said to be **adsorbed** (loosely held) on the colloid surface. Because these cations can *exchange places* with those moving freely about in the soil solution, the term **exchangeable ions** is also used to refer to the ions in this adsorbed state.

The colloid with its adsorbed cations is sometimes described as an **ionic double layer** in which the negatively charged colloid acts as a huge anion constituting the inner ionic layer, and the swarm of adsorbed cations constitutes the outer ionic layer (Figure 8.1). Because

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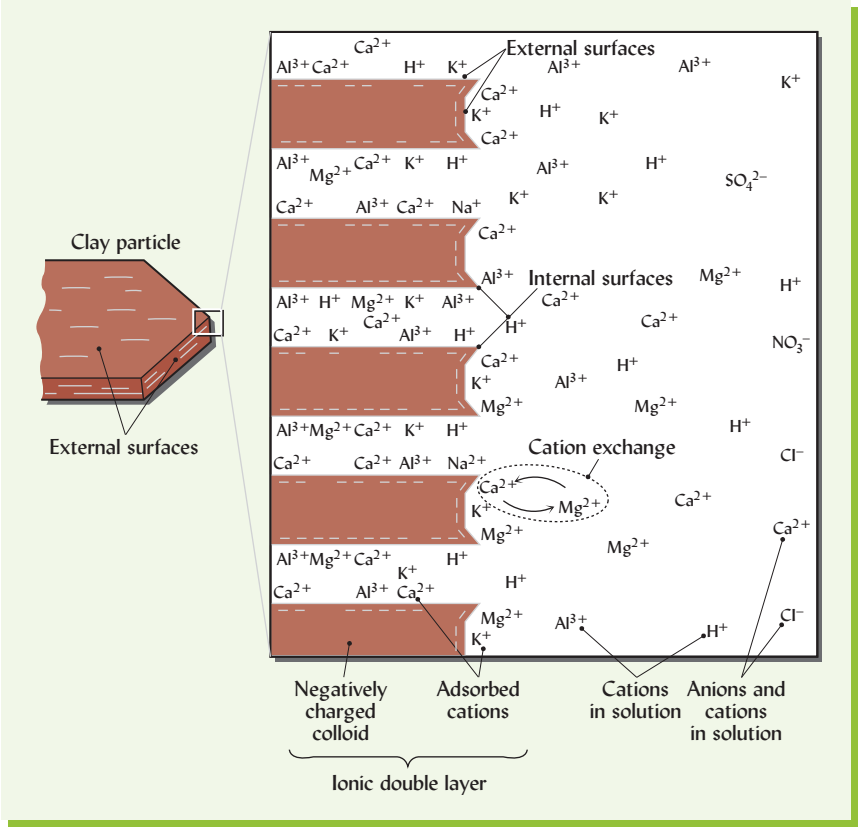

Figure 8.1 *Simplified representation of a silicate clay crystal, its complement of adsorbed cations, and ions in the surrounding soil solution. The enlarged view* (right) *shows that the clay comprises sheetlike layers with both external and internal negatively charged surfaces. The negatively charged particle acts as a huge anion and a swarm of positively charged cations is adsorbed to it because of attraction between charges of opposite sign. Cation concentration decreases with distance from the clay. Anions (such as* Cl^-, NO_3^-, *and* SO_4^{2-}*), which are repulsed by the negative charges, can be found in the bulk soil solution farthest from the clay* (far right). *Some clays (not shown) also exhibit positive charges that can attract anions.*

cations from the soil solution are constantly trading places with those that are adsorbed to the colloid, the ionic composition of the soil solution reflects that of the adsorbed swarm. For example, if Ca^{2+} and Mg^{2+} dominate the exchangeable ions, they will also dominate the soil solution. Under natural conditions, the proportions of specific cations present are largely influenced by the soil parent material and the degree to which the climate has promoted the loss of cations by leaching (see Section 9.1).

Anions such as Cl^-, NO_3^-, and SO_4^{2-} (also surrounded by water molecules, though, again, we do not show these water shells) may also be attracted to certain soil colloids that have *positive* charges on their surfaces. While adsorption of **exchangeable anions** is not as extensive as that for exchangeable cations, we shall see (Section 8.11) that it is an important mechanism for holding negatively charged constituents, especially in acid subsoils. When thinking about the colloids in soil, we should always keep in mind that they carry with them a complement of exchangeable cations and anions, along with certain other more tightly bound ions and molecules.

Adsorption of Water

In addition to adsorbing cations and anions, soil colloids attract and hold a large number of water molecules. Generally, the greater the external surface area of the soil colloids, the greater the amount of water held when the soil is air-dry (Figure 8.2). While this water may not be available for plant uptake (see Section 5.8), it does play a role in the survival of soil microorganisms, especially bacteria. The charges on the colloid surfaces attract the oppositely charged end of the polar water molecule. Some water molecules are attracted to the exchangeable cations, each of which is hydrated with a shell of water molecules. Water adsorbed between the clay layers can cause the layers to move apart, making the clay more plastic and swelling its volume (see Sections 4.9 and 8.14). As a soil colloid dries, water adsorbed on the external and internal surfaces is removed, so the particles and their constituent layers are brought closer together, shrinking the soil volume.

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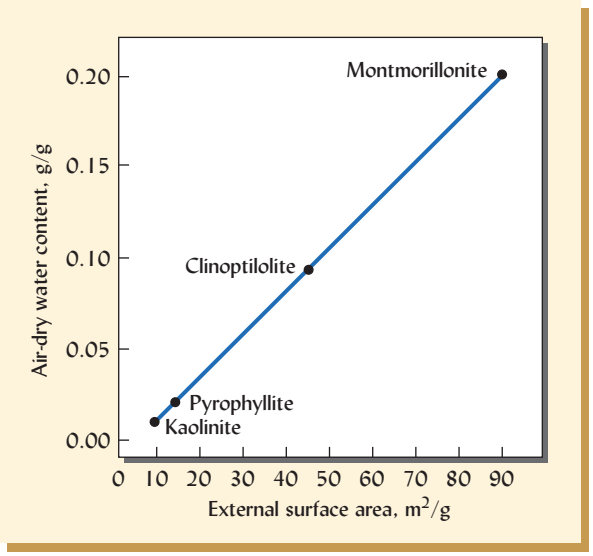

Figure 8.2 *The amount of water held in air-dry clay as influenced by the external surface area of the clay. The clays were dried in low-humidity air for 48 hours at 20 °C. The names refer to four silicate clay minerals that are characterized by differing amounts of external surface area per unit mass. Of the four, kaolinite and montmorillonite are by far the most common in soils and are discussed in detail in Section 8.2.* [Drawn from data in Morra et al. (1998)]

Types of Soil Colloids[1]

The colloids most important in soils can be grouped in four major types, each with its particular composition, structure, and properties (Table 8.1).

Crystalline Silicate Clays. These clays are the dominant type in most soils (except in Andisols, Oxisols, and Histosols—see Chapter 3). Their crystalline structure is layered much like pages in a book (clearly visible in Figure 8.3*a*). Each layer (page) consists of two to four

Table 8.1
MAJOR PROPERTIES OF SELECTED SOIL COLLOIDS

Colloid	Type	Size, μm	Shape	Surface area, m^2/g External	Surface area, m^2/g Internal	Interlayer Spacing,[a] nm	Net charge,[b] $cmol_c/kg$
Smectite	2:1 silicate	0.01–1.0	Flakes	80–150	550–650	1.0–2.0	−80 to −150
Vermiculite	2:1 silicate	0.1–0.5	Plates, flakes	70–120	600–700	1.0–1.5	−100 to −200
Fine mica	2:1 silicate	0.2–2.0	Flakes	70–175	—	1.0	−10 to −40
Chlorite	2:1 silicate	0.1–2.0	Variable	70–100	—	1.41	−10 to −40
Kaolinite	1:1 silicate	0.1–5.0	Hexagonal crystals	5–30	—	0.72	−1 to −15
Gibbsite	Al oxide	<0.1	Hexagonal crystals	80–200	—	0.48	+10 to −5
Goethite	Fe oxide	<0.1	Variable	100–300	—	0.42	+20 to −5
Allophane & Imogolite	Noncrystalline silicates	<0.1	Hollow spheres or tubes	100–1000	—	—	+20 to −150
Humus	Organic	0.1–1.0	Amorphous	Variable[c]	—	—	−100 to −500

[a]From the top of one layer to the next similar layer, 1 nm = 10^{-9} m = 10 Å.

[b]Centimoles of unbalanced or net charge per kilogram of colloid ($cmol_c/kg$), a measure of ion exchange capacity (see Section 8.9).

[c]It is very difficult to determine the surface area of organic matter. Different procedures give values ranging from 20 to 800 m^2/g.

[1]For a review of the structures and properties of the clays, see Meunier (2005), and for properties of clay and humus in soils, see Dixon and Weed (1989).

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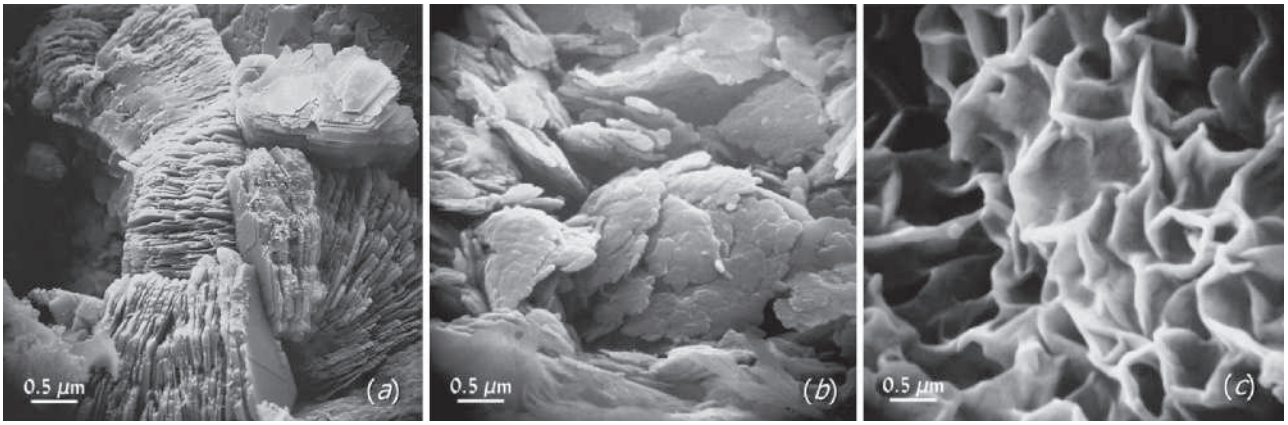

Figure 8.3 *Crystals of three silicate clay minerals.* (a) *Kaolinite (note hexagonal crystal at upper right).* (b) *A fine-grained mica.* (c) *Montmorillonite (a smectite group mineral).* (Bohor, B. F., and R. E. Hughes, 1971, Scanning electron microscopy of clays and clay minerals: Clays and Clay Minerals, v. 19, p. 49–54)

sheets of closely packed and tightly bonded oxygen, silicon, and aluminum atoms. Although all are predominately negatively charged, silicate clay minerals differ widely with regard to their particle shapes (**kaolinite**, a **fine-grained mica**, and a **smectite** are shown in Figure 8.3*a–c*), intensity of charge, stickiness, plasticity, and swelling behavior.

Noncrystalline Silicate Clays. These clays also consist mainly of tightly bonded silicon, aluminum, and oxygen atoms, but they do not exhibit ordered, crystalline sheets. The two principal clays of this type, **allophane** and **imogolite**, usually form from volcanic ash and are characteristic of Andisols (Section 3.7). They have high amounts of both positive and negative charge, and high water-holding capacities. Although malleable (plastic) when wet, they exhibit a very low degree of stickiness. Allophane and imogolite are also known for their extremely high capacities to strongly adsorb phosphate and other anions, especially under acid conditions.

Iron and Aluminum Oxides. These are found in many soils, but are especially important in the more highly weathered soils of warm, humid regions (e.g., Alfisols, Ultisols, and Oxisols). They consist mainly of either iron or aluminum atoms coordinated with oxygen atoms (the latter are often associated with hydrogen ions to make hydroxyl (OH) groups). Some, like **gibbsite** (an Al oxide) and **goethite** (an Fe oxide) consist of crystalline sheets. Other oxide minerals are noncrystalline, often occurring as **amorphous** coatings on soil particles. The oxide colloids are relatively low in plasticity and stickiness. Their net charge ranges from slightly negative to moderately positive. Although for simplicity we will use term *Fe, Al oxides* for this group, many are actually hydroxides or oxyhydroxides because of the presence of hydrogen ions.

Organic (Humus). Organic colloids are important in nearly all soils, especially in the upper parts of the soil profile. Humus colloids are not minerals, nor are they crystalline. Instead, they consist of a wide variety of partially decomposed cell walls and biomolecules derived mainly from microorganisms and bits of tissues derived mainly from plants (see Section 12.4). Much of this material has complex chains and rings of carbon atoms bonded to hydrogen, oxygen, and nitrogen. Humus particles are often among the smallest of soil colloids and exhibit very high capacities to adsorb water, but almost no plasticity or stickiness. Because humus is noncohesive, soils composed mainly of humus (Histosols) have very little bearing strength and are unsuitable for making building or road foundations. Humus has high amounts of both negative and positive charge per unit mass, but the net charge is always negative and varies with soil pH. The negative charge on humus is extremely high in neutral to alkaline soils.

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8.2 FUNDAMENTALS OF LAYER SILICATE CLAY STRUCTURE[2]

To understand why soils rich in, say, kaolinite clay, behave so very differently from soils dominated by, say, montmorillonite clay, it is necessary to know something about the silicate clay minerals. We will begin by examining the main building blocks from which the layer silicates are constructed, then consider the particular arrangements that give rise to the critically important surface charges.

Silicon Tetrahedral and Aluminum–Magnesium Octahedral Sheets[2]

The most important silicate clays are known as **phyllosilicates** (Greek *phyllon*, leaf) because of their leaflike or planar structure. As shown in Figure 8.4, they are composed of two kinds of horizontal **sheets**.

Tetrahedral Sheets. This kind of sheet consists of two **planes** of oxygens with mainly silicon in the spaces between the oxygens. The basic building block for the tetrahedral sheet is a unit composed of one silicon atom surrounded by four oxygen atoms. It is called a **tetrahedron** because (as shown in Figure 8.4, *top left*) the oxygens define the apices of a *four*-sided geometric solid that resembles a pyramid (having three "sides" and a bottom). An interlock-

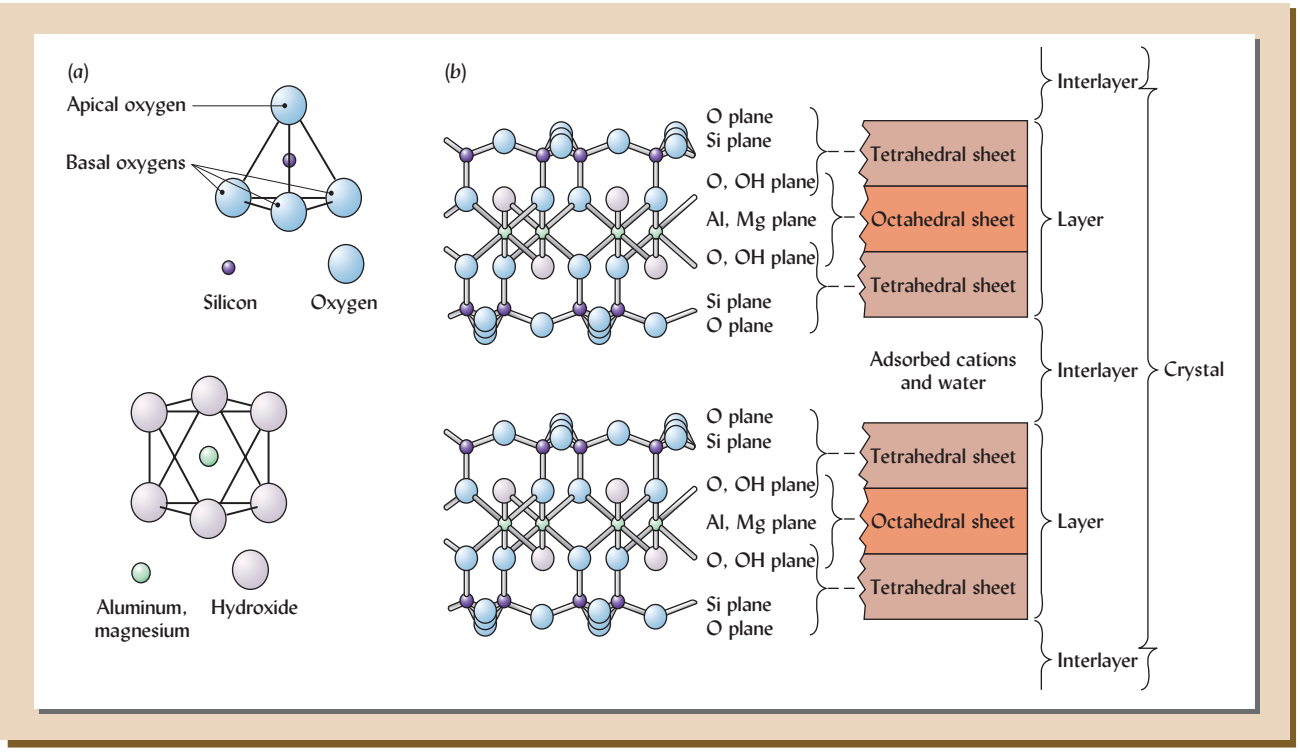

Figure 8.4 *The basic structural components of silicate clays.* (a) *A single* tetrahedron, *a four-sided building block composed of a silicon ion surrounded by four oxygen atoms; and a single eight-sided* octahedron, *in which an aluminum (or magnesium) ion is surrounded by six oxygen atoms or hydroxy groups.* (b) *In clay crystals thousands of these tetrahedral and octahedral building blocks are connected to give planes of silicon and aluminum (or magnesium) ions. These planes alternate with planes of oxygen atoms and hydroxy groups. Note that apical oxygen atoms are common to adjoining tetrahedral and octahedral sheets. The silicon plane and associated oxygen–hydroxy planes make up a* tetrahedral sheet *Similarly, the aluminum–magnesium plane and associated oxygen–hydroxy planes constitute the* octahedral sheet. *Different combinations of tetrahedral and octahedral sheets are termed* layers. *In some silicate clays these layers are separated by* interlayers *in which water and adsorbed cations are found. Many layers are found in each* crystal.

[2]The authors are indebted to Dr. Darrel G. Schultze of Purdue University for kindly providing structural models for the silicate clay minerals.

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ing array of such tetrahedra, each sharing its basal oxygens with its neighbor, make a **tetrahedral sheet**.

Octahedral Sheets. Six oxygen atoms coordinating with a central aluminum or magnesium atom form the shape of an *eight*-sided geometric solid, or **octahedron**. Numerous octahedra linked together horizontally constitute the **octahedral sheet**. There are variations on the octahedral sheet. If *three* Mg^{2+} atoms are coordinated with (and balance the charges on) the six oxygens/hydroxyls, then the sheet is called a ***tri*octahedral** sheet. If, instead, the six oxygens/hydroxyls are coordinated with *two* Al^{3+} atoms, then the sheet is called ***di*octahedral**. Note that the distinction is based on the number of metal atoms required to satisfy the six negative charges from the oxygen/hydroxyls (see Figure 8.5, *left* and *middle*). As we will see later, numerous intergrades are possible in which both 2+ and 3+ cations are present.

The tetrahedral and octahedral sheets are the fundamental structural units of silicate clays. Two to four of these sheets may be stacked together in sandwich-like arrangements, with adjacent sheets strongly bound together by sharing some of the same oxygen atoms (see Figure 8.4). The specific nature and combination of sheets in these layers vary from one type of clay to another and largely control the physical and chemical properties exhibited. The relationship between *planes*, *sheets*, and *layers* shown in Figure 8.4 should be carefully studied.

The structural arrangements just described suggest a very simple relationship among the elements making up silicate clays. In nature, however, clays have formulas that are more complex. During the weathering of rocks and minerals, many different elements are present in the weathering solution. As clay minerals or their precursors crystallize, cations of similar size (see Table 8.2) may substitute for silicon, aluminum, and magnesium ions in the respective tetrahedral and octahedral sheets.

Note from Table 8.2 that aluminum is only slightly larger than silicon. Consequently, aluminum can fit into the center of the tetrahedron in the place of the silicon without much change in the basic structure of the crystal. This process by which one element fills a position usually filled by another of similar size is called **isomorphous substitution**. Isomorphous substitution can also occur in the octahedral sheets. For example, iron and zinc ions are not much different in size from aluminum and magnesium ions (Table 8.2). Any of these ions can fit in the central position of an octahedron. In some layer silicates, isomorphous substitution occurs in both tetrahedral and in octahedral sheets.

Source of Charges

Isomorphous substitution is of vital importance because it is the primary source of both negative and positive charges of silicate clays. For example, the Mg^{2+} ion is only slightly larger than the Al^{3+} ion, but it has one less positive charge. If a Mg^{2+} ion substitutes for an Al^{3+} ion in a dioctahedral sheet, there will be insufficient positive charges to balance the negative

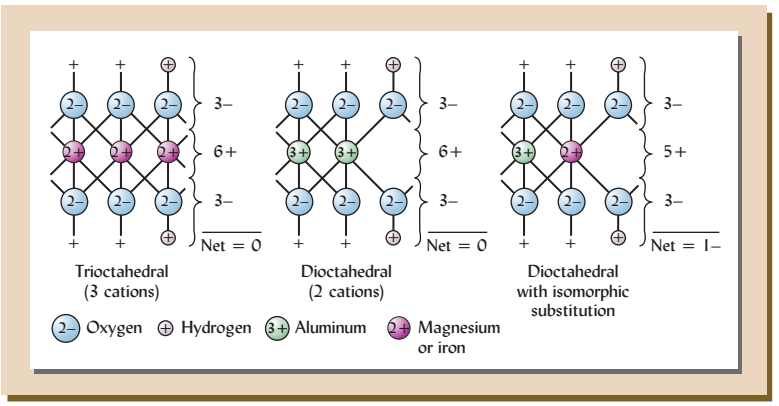

Figure 8.5 *Silicate mineral* tri- *and* dioctahedral *structures and isomorphous substitution. For each oxygen atom, one of the two − charges is balanced by a + charge from either a* H^+ *(making a hydroxyl group) or from a Si atom in the tetrahedral sheet (not shown, but represented by a +). In a* trioctahedral *sheet* (left) *three out of three octahedral positions are occupied by a metal cation with a 2+ charge (typically either* Fe^{2+} *or* Mg^{2+}*). The + and − charges are balanced so there is no net charge. Biotite is an example of trioctahedral clay. In a* dioctahedral *sheet* (middle) *only two out of three octahedral positions are occupied, but by a metal cation with a 3+ charge (*Al^{3+} *is most common). Again, the + and − charges are balanced so there is no net charge on the octahedral sheet. Muscovite is an example of dioctahedral clay. In the dioctahedral sheet shown on the right, a* Mg^{2+} *atom occupies one of the positions normally occupied by an* Al^{3+} *atom, thus leaving a 1− net charge on the sheet.* (Diagram courtesy of Ray R. Weil)

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Table 8.2
IONIC RADII AND LOCATION OF ELEMENTS FOUND IN SILICATE CLAYS ISOMORPHOUS SUBSTITUTION

Ion	Radius, nm (10^{-9} m)	Found in
Si^{4+}	0.042	Tetrahedral sheet
Al^{3+}	0.051	Tetrahedral sheet
Fe^{3+}	0.064	Octahedral sheet
Mg^{2+}	0.066	Octahedral sheet
Zn^{2+}	0.074	Exchange or interlayer sites
Fe^{2+}	0.076	Exchange or interlayer sites
Na^{+}	0.095	Exchange or interlayer sites
Ca^{2+}	0.099	Exchange or interlayer sites
K^{+}	0.133	Exchange or interlayer sites
O^{2-}	0.140	Both sheets
OH^{-}	0.155	Both sheets

charges from the oxygens; hence, the lattice is left with a −1 net charge (see Figure 8.5, *right*). Similarly, every Al^{3+} that substitutes for a Si^{4+} in a tetrahedral sheet creates a net negative charge at that site because the negative charges from the four oxygens will be only partially balanced. In a trioctahedral sheet, if an Al^{3+} substitutes for the usual Mg^{2+} or Fe^{2+}, then a net *positive* charge is created. The net charge associated with a clay crystal is the sum of the positive and negative charges. In most silicate clays, the negative charges predominate (as will be discussed in Section 8.8). As we shall see (Sections 8.3 and 8.6), additional, more temporary charges can also develop on the edges of the tetrahedral and octahedral surfaces.

8.3 MINERALOGICAL ORGANIZATION OF SILICATE CLAYS

Based on the number and arrangement of tetrahedral (Si) and octahedral (Al, Mg, Fe) sheets contained in the crystal units or layers, crystalline clays may be classed into two main groups: **1:1 silicate clays**, in which each layer contains *one* tetrahedral and *one* octahedral sheet, and **2:1 silicate clays**, in which each layer has *one* octahedral sheet sandwiched between *two* tetrahedral sheets.

1:1-Type Silicate Clays

Kaolinite is by far the most common 1:1 silicate clay in soils (others include *halloysite*, *nacrite*, and *dickite*). As implied by the term *1:1 silicate clay*, each kaolinite layer consists of one silicon tetrahedral sheet and one aluminum octahedral sheet. The two types of sheets are tightly held together because the apical oxygen atom (the oxygen atom that forms the apex or tip of the "pyramid") in each tetrahedron also forms a bottom corner of one or more of the octahedra in the adjoining sheet (Figure 8.6). Note that because a kaolinite crystal layer consists of these two sheets, it exposes a plane of oxygen atoms on the bottom surface, but a plane of hydroxyls on the upper surface.

This arrangement has two very important consequences. First, as will be discussed in Section 8.6, where the hydroxyl plane is exposed on the clay particle surface, removal or addition of hydrogen ions can produce either positive or negative charges, depending on the pH of the soil. The exposed **hydroxylated surface** can also react with and strongly bind specific anions. Second, when the layers consisting of alternating tetrahedral and octahedral sheets are stacked on top of one another, the hydroxyls of the octahedral sheet in one layer are adjacent

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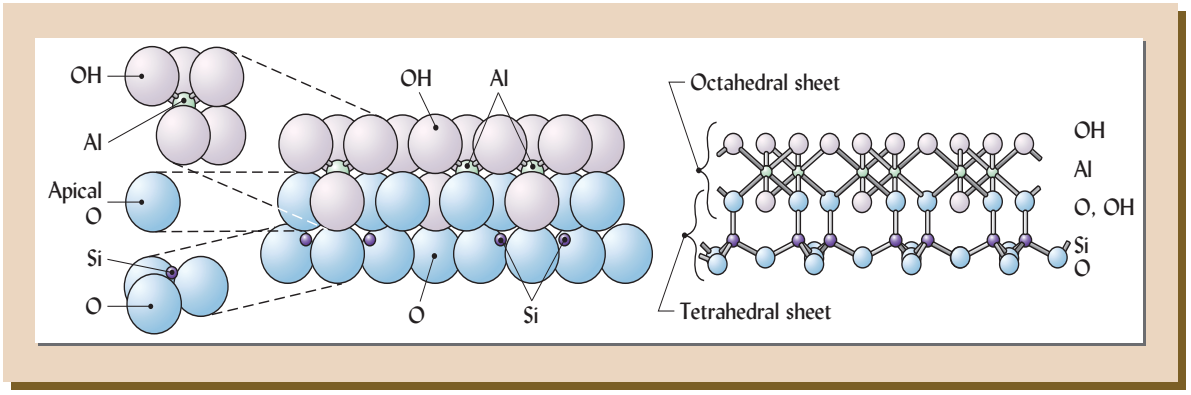

Figure 8.6 *Models of the 1:1-type clay kaolinite. The primary elements of the octahedral* (upper far left) *and tetrahedral* (lower far left) *sheets are depicted as they might appear separately. Note a kaolinite layer consists of adjacent octahedral and tetrahedral sheets—hence, the designation 1:1. The octahedral and tetrahedral sheets are bound together* (center) *by mutually shared (apical) oxygen atoms. The result is a layer with hydroxyls on one surface and oxygens on the other. To permit us to view the front silicon atoms, we have not shown some basal oxygen atoms that are normally present. The diagram at right shows the bonds between atoms. The kaolinite mineral is comprised of a stacked series of these flat layers tightly held together with no interlayer spaces.*

to the basal oxygens of the tetrahedral sheet of the next layer. Therefore, adjacent layers are bound together by **hydrogen bonding** (see Section 5.1).

Because of the interlayer hydrogen bonding, the structure of kaolinite is fixed, and no expansion can occur between the layers when the clay is wetted. Cations and water generally do not enter between the structural layers of a 1:1 mineral particle. The effective surface of kaolinite is thus restricted to its outer faces or external surface area. This fact and the lack of significant isomorphous substitution in this mineral account for the relatively small capacity of kaolinite to adsorb exchangeable cations (see Table 8.1).

Kaolinite crystals are usually hexagonal in shape (see Figure 8.3*a*) and larger than most other clays (Table 8.1). Compared to some 2:1 silicate clays, 1:1 clays like kaolinite exhibit less plasticity, stickiness, cohesion, shrinkage, and swelling and can also hold less water (Figure 8.2). Because of these properties, soils dominated by 1:1 clays are relatively easy to cultivate for agriculture and, with proper nutrient management, can be quite productive. Kaolinite-containing soils are well suited for use in roadbeds and building foundations (Figure 8.7). The nonexpanding 1:1 structure gives kaolinite clays properties good for making bricks and ceramics and for many other uses (see Box 8.1).

Figure 8.7 *A road in southeastern Tanzania crossing a large valley comprised of black soils high in expansive 2:1 clays. A stable roadbed was built up by trucking the red colored soil material seen in the foreground. This soil material came from distance uplands where the soils were better drained, more weathered, and dominated by the 1:1 clay mineral kaolinite. The black soils adjacent to the road would have been much more conveniently and inexpensively used, but their high content of 2:1 clays made them completely unsuitable for a road base. The 2:1 clays shrink in dry weather and swell up in wet weather and thus would have cause rapid heaving and cracking of the pavement.* (Photo courtesy of Ray R. Weil)

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BOX 8.1

KAOLINITE CLAY—THE STORY OF WHITE GOLD[a]

Kaolinite, the most common of the 1:1 clay minerals, has been used for thousands of years to make pottery, roofing tiles, and bricks. The basic processes have changed little to this day. The clayey material is saturated with water, kneaded, and molded or thrown on a potter's wheel to obtain the desired shape, and then hardened by drying or firing (Figures 8.8 and 8.9). The mass of cohering clay platelets hardens irreversibly when fired and the nonexpanding nature of kaolinite allows it to be fired without cracking from shrinkage. The heat also changes the typical gray color of the soil material to "brick red" because of the irreversible oxidation and crystallization of the iron–oxyhydroxides that often coat soil kaolinite particles. In contrast, kaolinite mined from pure deposits fires to a light, creamy color. Kaolinite is not as plastic (moldable) as some other clays, however, and so is usually mixed with more plastic types of clays for making pottery.

Figure 8.8 *In highly weathered regions of the world, people dig up kaolinitic clay soil, mix it with water, mold it into blocks, dry the block in the sun, and then stack them to form a kiln by which they are fired to make bricks.* (Photo courtesy of Ray R. Weil)

It was in seventh-century China that pure kaolinite deposits were first used to make objects of a translucent, lightweight, and strong ceramic called porcelain. The name *kaolinite* derives from the Chinese words *kao* and *ling*, meaning "high ridge," as the material was first mined from a hillside in Kiangsi Province. The Chinese held a monopoly on porcelain-making technology (hence the term *china* for porcelain dishes) until the early 1700s. English colonists, in what is now Georgia in the United States, noted outcrops of white kaolinite clay in areas of rather unproductive soil. The colonialists soon were exporting this kaolinite as the main ingredient for making porcelain in England, where the now-famous pottery was first manufactured from the Georgia kaolinite clay. Sometimes called "white Georgia dirt," pure white kaolinite is still sold locally in rural Georgia (and now online, e.g., at whitedirt.samsbiz.com/) for purposes ranging from geophagy (see Box 1.1) to shampooing hair.

The market for pure, white kaolinite clay greatly expanded when paper manufacturers started using kaolinite clay to make sizing, the coating that makes high-quality papers smoother, whiter, and more printable. Other industrial uses now include paint pigments, fillers in plastic

Figure 8.9 *Kaolinite clay in African pottery and early nineteenth-century English china* (inset). (Photo courtesy of Ray R. Weil)

Figure 8.10 *A milky slurry of water and kaolin clay sprayed on leaves and fruits has been shown to protect crops against numerous insects, pest, and fungal pathogens.* (Photo courtesy of Ray R. Weil)

[a]For more on social and commercial aspects of kaolinite, see Seabrook (1995) and Windham (2007). For information on kaolin as pest barrier see Reddy (2013).

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BOX 8.1

KAOLINITE CLAY—THE STORY OF WHITE GOLD[a] *(CONTINUED)*

manufacture, and ceramic materials used for electrical insulation and heat shielding (as on the belly of the space shuttle). The kaolinite in kaopectin-type medications lines the stomach walls and inactivates diarrhea-causing bacteria by adsorbing them on the clay particle surfaces.

A development that is likely to increase the demand for kaolinite is its use as a spray-on coating for leaves and fruits such as apples, peaches, tomatoes that provides a nontoxic (approved for organic farming) physical barrier to protect from insect pests and fungal diseases (Figure 8.10). All these uses have made industrial kaolinite clay mining a big business in Georgia. Unfortunately, surface mining of kaolinite to meet these needs has sometimes caused both environmental and social disruptions.

Expanding 2:1-Type Silicate Clays

The four general groups of 2:1 silicate clays are characterized by *one* octahedral sheet sandwiched between *two* tetrahedral sheets. Two of these groups, **smectite** and **vermiculite**, include expanding-type minerals; the other two, **fine-grained micas (illite)** and **chlorite**, are relatively nonexpanding.

Smectite Group. The flake-like crystals of smectites (see Figure 8.3*c*) have a high amount of mostly negative charge resulting from isomorphous substitution. Most of the charge derives from Mg^{2+} ions substituted in the Al^{3+} positions of the octahedral sheet, but some also derives from substitution of Al^{3+} ions for Si^{4+} in the tetrahedral sheets (Figure 8.11). Because of these substitutions, the capacity to adsorb cations is very high—about 20–40 times that of kaolinite.

In contrast to kaolinite, smectites have a 2:1 structure that exposes a layer of oxygen atoms at both the top and bottom planes. Therefore, adjacent layers are only loosely bound to each other by very weak oxygen-to-oxygen and cation-to-oxygen linkages and the space between is variable (Figure 8.11). The internal surface area exposed between the layers by far exceeds the external surface area of these minerals and contributes to the very high total **specific surface area** (Table 8.1). Exchangeable cations and associated water molecules are attracted to the spaces between the interlayer spaces.

Flake-like smectite crystals tend to pile upon one another, forming wavy stacks that contain many extremely small *ultramicropores* (see Figure 8.12 and Table 4.6). When soils high in smectite are wetted, adsorption of water in these ultramicropores leads to significant swelling; when they re-dry, the soils shrink in volume (see Section 4.9). The expansion upon wetting contributes to the high degree of

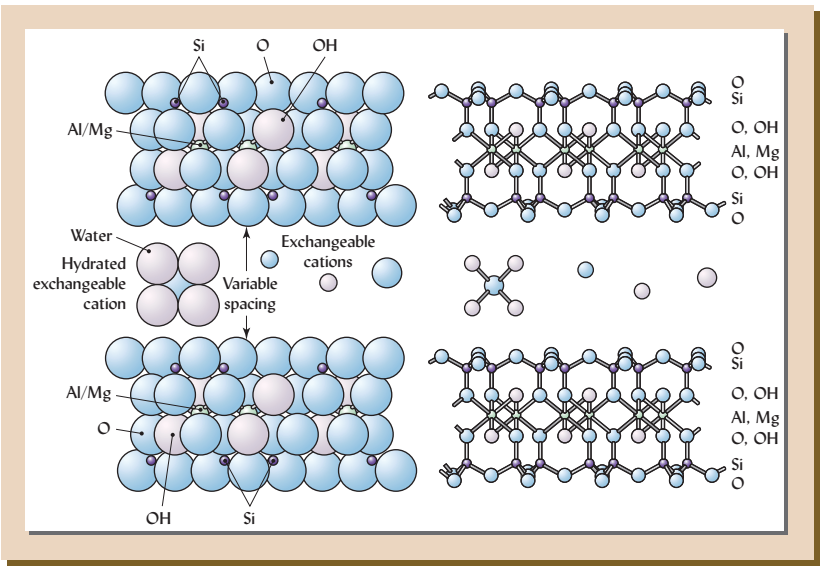

Figure 8.11 *Model of two crystal layers and an interlayer characteristic of montmorillonite, a smectite expanding lattice 2:1-type clay mineral. Each layer is made up of an octahedral sheet sandwiched between two tetrahedral sheets with shared apical oxygen atoms. There is little attraction between oxygen atoms in the bottom tetrahedral sheet of one unit and those in the top tetrahedral sheet of another. This permits a variable space between layers, which is occupied by water and exchangeable cations. The internal surface area thus exposed far exceeds the surface around the outside of the crystal. Note that magnesium has replaced aluminum in some sites of the octahedral sheet. Likewise, some silicon atoms in the tetrahedral sheet may be replaced by aluminum (not shown). These substitutions give rise to a negative charge, which accounts for the high cation exchange capacity of this clay mineral. A ball-and-stick model of the atoms and chemical bonds is at the right.*

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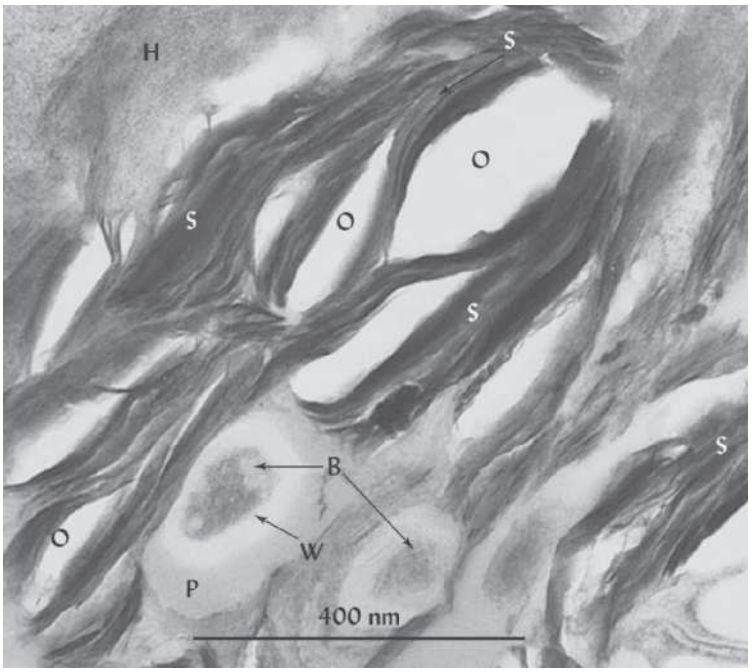

Figure 8.12 *Transmission electron micrograph of a portion of an undisturbed microaggregate of soil, showing smectite clay (S), bacterial cells (B), and polysaccharides (P). Dark stacks of parallel crystals of smectite clay form an open, wavy, clay ultrastructure in which ultramicropores (O) are visible as white areas. Water drawn into the ultramicropores between the clay substacks accounts for most of the swelling of smectite clay upon wetting. It is less likely, as was once thought, that water causes swelling by entering the interlayers between smectite clay crystal units.* (Image courtesy of M. Thompson, T. Pepper, and A. Carmo, Iowa State University)

plasticity, stickiness, and cohesion that make smectitic soils very difficult to cultivate or excavate. Wide cracks commonly appear during the drying of smectite-dominated soils (such as Vertisols, Figure 3.31). The shrink/swell behavior makes smectitic soils quite undesirable for most construction activities, but they are well suited for a number of applications that require a high adsorptive capacity and the ability to form seals of very low permeability (see Box 8.2). **Montmorillonite** is the most prominent of the smectites in soils, although others are also found.

Vermiculite Group. The most common **vermiculites** are 2:1-type minerals in which the octahedral sheet is aluminum dominated (dioctahedral), but some magnesium-dominated (trioctahedral) vermiculites also exist. The tetrahedral sheets of most vermiculites have considerable substitution of aluminum in the silicon positions, giving rise to a cation exchange capacity (CEC) that usually exceeds that of all other silicate clays, including smectites (Table 8.1).

The interlayer spaces of vermiculites usually contain strongly adsorbed water molecules, Al-hydroxy ions, and cations such as magnesium (Figure 8.13). However, these interlayer constituents act primarily as bridges to hold the units together, rather than wedges driving them apart. The degree of swelling and shrinkage is, therefore, considerably less for vermiculites than for smectites. For this reason, vermiculites are considered limited-expansion clays, expanding more than kaolinite, but much less than the smectites.

Nonexpanding 2:1 Silicate Minerals

The main nonexpanding 2:1 minerals are the **fine-grained micas** and the **chlorites**. We will discuss the fine-grained micas first.

Mica Group. Biotite and muscovite are examples of unweathered micas typically found in the sand and silt fractions. The more weathered **fine-grained micas**, such as **illite** and **glauconite**, are found in the clay fraction of soils. Their 2:1-type structures are quite similar to those of their unweathered cousins. Unlike in smectites, the main source of charge in fine-grained micas is the substitution of Al^{3+} in about 20% of the Si^{4+} sites in the tetrahedral sheets. This results in a high net negative charge in the tetrahedral sheet, even higher than that found in vermiculites. The negative charge attracts cations, among which potassium (K^+) is just the right size to fit snugly into certain hexagonal "holes" between the tetrahedral oxygen groups (Figures 8.13 and 8.16) and thereby get very close to the negatively charged sites.

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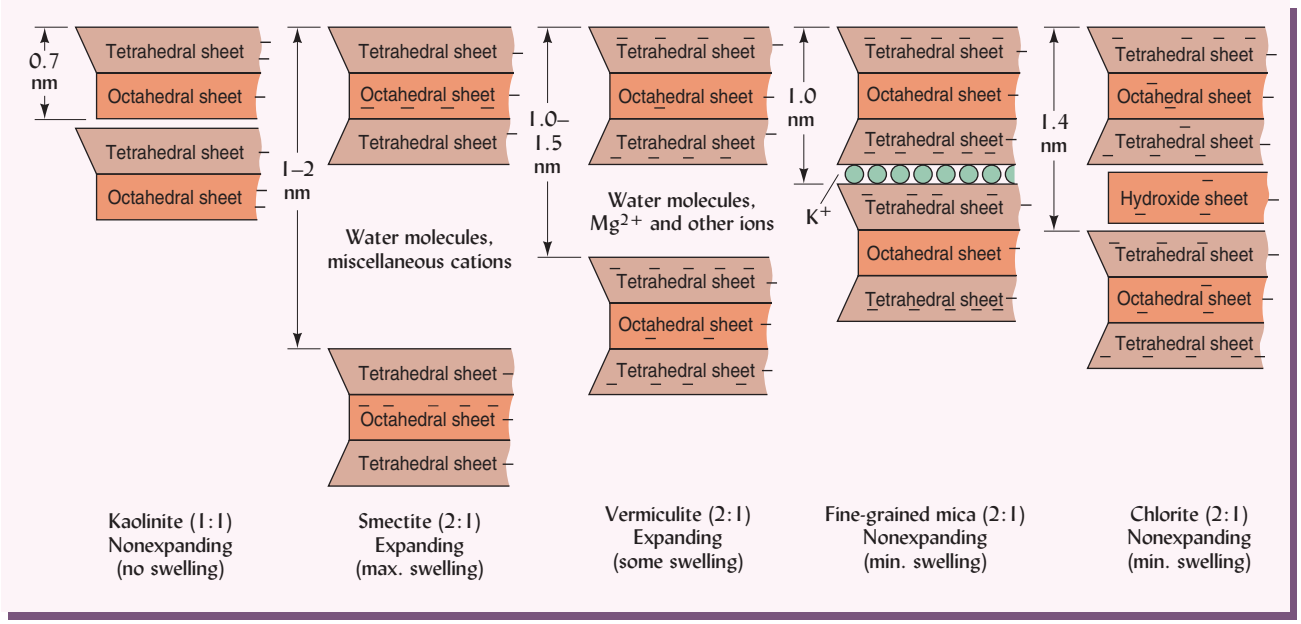

Figure 8.13 *Schematic drawing illustrating the organization of tetrahedral and octahedral sheets in one 1:1-type mineral (kaolinite) and four 2:1-type minerals. The octahedral sheets in each of the 2:1-type clays can be either aluminum dominated (dioctahedral) or magnesium dominated (trioctahedral). However, in most chlorites the trioctahedral sheets are dominant while the dioctahedral sheets are generally most prominent in the other three 2:1 types. Note that kaolinite is nonexpanding, the layers being held together by hydrogen bonds. Maximum interlayer expansion is found in smectite, with somewhat less expansion in vermiculite because of the moderate binding power of numerous Mg^{2+} ions. Fine-grained mica and chlorite do not expand because K^+ ions (fine-grained mica) or an octahedral-like sheet of hydroxides of Al, Mg, Fe, and so forth (chlorite) tightly bind the 2:1 layers together. The interlayer spacings are shown in nanometers (1 nm = 10^{-9} m).*

BOX 8.2

ENVIRONMENTAL USES OF SMECTITE-TYPE EXPANDING CLAYS[a]

The chemical and physical properties of smectite-type clays make them extremely useful in certain environmental engineering applications. A common use of swelling clays—especially a mined mixture of smectite clays called bentonite—is as a sealant layer placed on the bottom and sides of ponds, waste lagoons, and landfill cells (Figure 8.14). The clay material expands when wetted and forms a highly impermeable barrier to the movement of water as well as organic and inorganic contaminants contained in the water. The contaminants are thus held in the containment structure and prevented from polluting the groundwater.

A more exotic use for swelling clays is proposed in Sweden for the final repository of that country's highly radioactive and toxic nuclear power plant wastes. The plan is to place the wastes in large (about 5 m × 1 m) copper canisters and bury them deep underground in chambers carved from solid rock. As a final defense against leakage of the highly toxic material to the groundwater, the canisters will be surrounded by a thick buffer layer of bentonite clay. The clay is packed dry around the canisters and is expected to absorb water to saturation during the first century of storage, thus gradually swelling into a sticky, malleable mass that will fill any cavities or cracks in the rock. The clay buffer will serve three protective functions: (1) cushion the canister against small (10-cm) movements in

Figure 8.14 *A large waste lagoon under construction is being lined with a layer of dark-colored smectitic clay. The very low hydraulic conductivity of the expansive clay will seal in the stored liquid and retard percolation of polluted water. The high CEC of the clay will retard leaching of pollutants by retaining dissolved pollutants, even when some water movement takes place. Straw-colored erosion blankets are also being used to establish erosion controlling grasses on the berms.* (Photo by Ray R. Weil)

(continued)

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BOX 8.2

ENVIRONMENTAL USES OF SMECTITE-TYPE EXPANDING CLAYS *(CONTINUED)*

the rock formation, (2) form a seal of extremely low permeability to keep corrosive substances in the groundwater away from the canister, and (3) act as a highly efficient electrostatic filter (see Section 8.8) to adsorb and trap cationic radionuclides that might leak from the canister in some far future time.

Figure 8.15 shows how bentonite is used as a plug or sealant to prevent leakage around an environmental groundwater monitoring well. For most of the well depth, the gap between the bore hole wall and the well tube is back-filled with sand to support the tube and allow vertical movement of the groundwater to be sampled. About 30 cm below the soil surface, the space around the well casing is filled instead with air–dry granulated bentonite (white substance being poured from bucket in the photograph). As the bentonite absorbs water, it swells markedly, taking on an almost rubbery consistency and forming an impermeable seal that fits tightly against both the well casing and the soil bore hole wall. This seal prevents contaminants in or on the surface soil from leaking down the outside of the well casing. In the case of groundwater contaminated with volatile organics like gasoline, the bentonite also prevents vapors from escaping without being properly sampled.

Increasingly, environmental scientists are using swelling-type clays for the removal of organic chemicals from water by partitioning (see Section 8.12). For example, where there has been a spill of toxic organic chemicals, a deep trench may be dug across the slope and back-filled with a slurry of smectite clay and water to intercept a plume of polluted water. The swelling nature of the smectites prevents the rapid escape of the contaminated water while the highly reactive colloid surfaces chemically sorb the contaminants, purifying the groundwater as it slowly passes by. Chapter 18 takes a more detailed look at such "slurry walls" and other soil technologies for cleaning the environment.

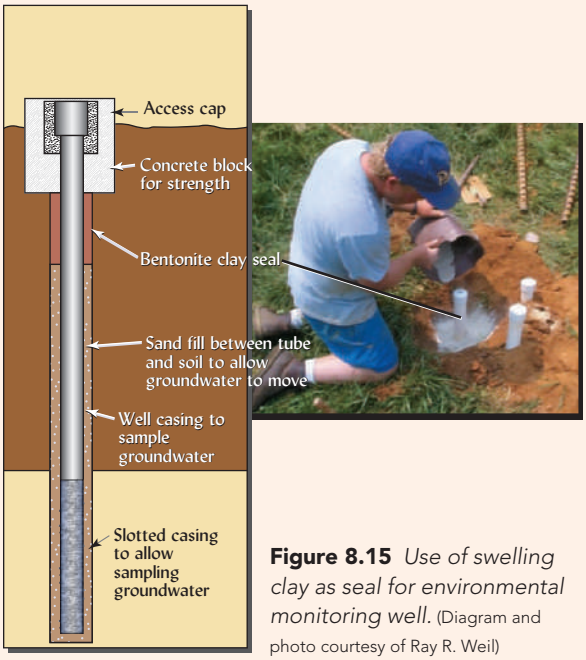

Figure 8.15 *Use of swelling clay as seal for environmental monitoring well.* (Diagram and photo courtesy of Ray R. Weil)

[a]For more detailed information on environmental use of swelling clays, see Reid and Ulery (1998). For details of the Swedish nuclear repository use of bentonite, see Swedish Nuclear Power Inspectorate (2005) and S.K.B. (2004).

By their mutual attraction for the K^+ ions in between, adjacent layers in fine-grained micas are strongly bound together. Hence, the fine-grained micas are quite **nonexpansive**. Because of their nonexpansive character, the fine-grained micas are more like kaolinite than smectites with regard to their capacity to adsorb water and their degree of plasticity and stickiness.

Chlorites. In most soil **chlorites**, iron or magnesium, rather than aluminum, occupy many of the octahedral sites. Commonly, a magnesium-dominated trioctahedral hydroxide sheet is sandwiched in between adjacent 2:1 layers (Figure 8.11). Thus, chlorite is sometimes said to have a 2:1:1 structure. Chlorites are nonexpansive because the hydroxylated surfaces of an intervening Mg-octahedral sheet are hydrogen-bonded to the oxygen atoms of the two adjacent tetrahedral sheets, binding the layers tightly together. The colloidal properties of the chlorites are therefore quite similar to those of the fine-grained micas (Table 8.1).

X-Ray Diffraction Analysis

Until the invention of suitable means of investigating mineral structure at the atomic level, it was thought that clays consisted of inert mineral fragments coated in amorphous gels of iron oxides. Now, the relative amounts of various types of clay minerals present in a soil can be determined by a procedure called **X-ray diffraction analysis**, which measures the distance between layers (the **d-spacing**) in the mineral structure (see Box 8.3).

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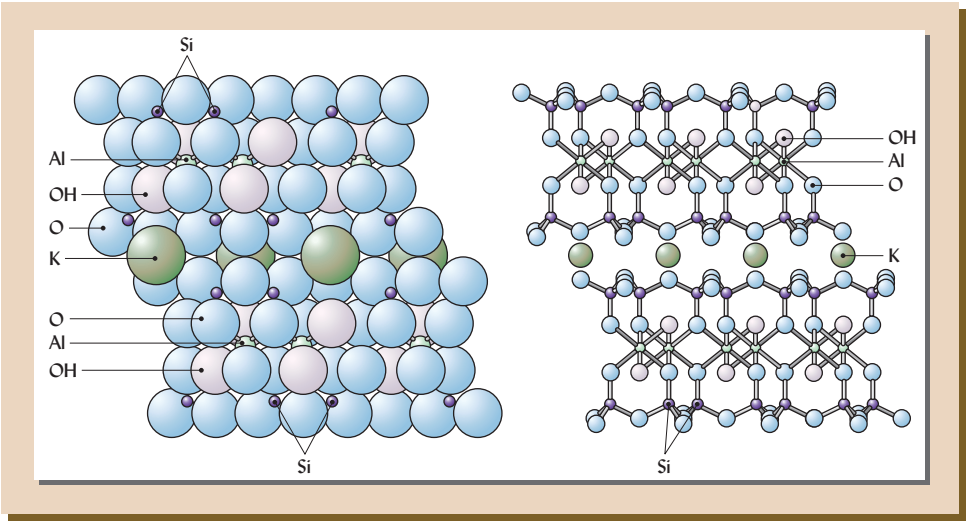

Figure 8.16 *Model of a 2:1-type nonexpanding lattice mineral of the fine-grained mica group. The general constitution of the layers is similar to that in the smectites, one octahedral sheet between two tetrahedral sheets. However, potassium ions are tightly held between layers, giving the mineral a more or less rigid type of structure that prevents the movement of water and cations into the space between layers. The internal surface and cation exchange capacity of fine-grained micas thus are far below those of the smectites.*

BOX 8.3

X-RAYS UNLOCK THE MYSTERIES OF CRYSTALLINE CLAY STRUCTURE

When a thin smear of clay powder or paste is slowly rotated in an X-ray beam of a particular wavelength, the X-ray waves reflecting off parallel planes of atoms in the clay crystal create a diffraction pattern that can be detected by X-ray diffraction analysis. The detected X-ray energy is low when the waves bouncing off different layers are out of phase and therefore cancel each other out. The detected energy is magnified when the waves reflected from two layers are in phase (synchronous) and therefore reinforce each other (Figure 8.17, *left*). These reinforced waves create peaks of energy, which are recorded on a graph called a **diffractogram**.

When incoming waves strike two (or more) parallel surfaces, the angle of incidence theta (θ) will determine how much farther the waves striking the second layer must travel compared to those striking the first layer. **Bragg's law** tells us there is a specific angle that will cause the waves striking the second layer to travel an additional distance exactly equal to their wavelength. Therefore, the waves reflected off the second layer will be in phase with those reflected off the first layer. The distance (d, in nm) between layers is calculated from Bragg's law:

$$n\lambda = 2d \sin \theta \qquad (8.1)$$

where n is an integer, λ is the known wavelength (in nm) of the X-rays, and θ is the glancing angle that causes the waves reflected from different layers to reinforce each other.

Layers at specific distances apart characterize the crystal structure for each clay mineral (note the nanometer d-spacings shown in Figure 8.13), so one can determine which minerals are present by examining the specific angles that cause reinforced X-ray energy peaks. The sizes of the X-ray peaks are semiquantitatively related to the relative amount of a specific mineral present. X-ray diffraction can best identify clay structures if the clay is given special pretreatments by saturating it with specific cations, washing it with various solvents, or heating it to remove interlayer impurities.

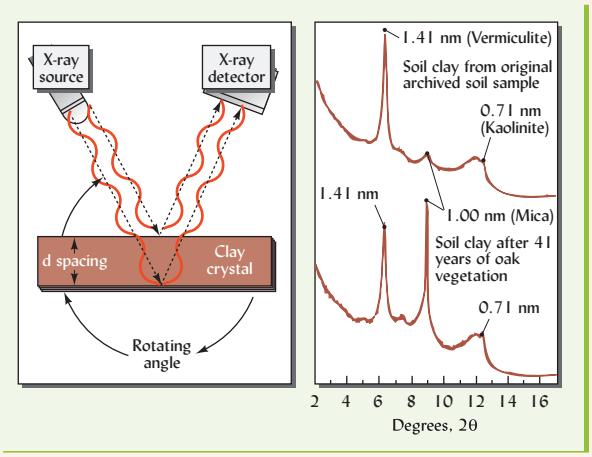

Figure 8.17 *A simplified diagram of X-ray diffraction used to identify clay minerals* (left) *and two X-ray diffractograms* (right) *showing peaks indicative of vermiculite, fine-grained mica, and kaolinite clay minerals.* [Diffractograms redrawn from Tice et al. (1996), diagram courtesy of Ray R. Weil]

Figure 8.17 (*right*) shows two diffractograms that suggest the presence of mainly fine-grained mica, vermiculite, and kaolinite clays. The diffractograms shown are from a long-term experiment in the San Demas Mountains of southern California, USA. Scientists began by digging special

(continued)

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BOX 8.3

X-RAYS UNLOCK THE MYSTERIES OF CRYSTALLINE CLAY STRUCTURE *(CONTINUED)*

pits (called lysimeters) fit with drains that allowed leaching water to be collected. Each pit was then uniformly packed full with soil material of known composition. Oak trees (*Quercus dumosa*) were planted in some of the lysimeters. After 41 years, the surface layer of soil was sampled and compared to archived samples of the original soil material. Both X-ray diffractograms showed a distinct peak for the 1.41-nm interlayer spacing characteristic of vermiculite. However, a strong peak for 1.0-nm spacing (characteristic of mica) appeared only in the soil under oak forest. Chemical analyses showed that the oak trees had increased the amount of potassium in the A horizon by cycling this element up from the deeper layers (see Section 2.5). Together, these two diffractograms illustrate: (1) the utility of X-ray diffraction as a tool for identifying clay minerals and (2) the chemical alteration processes by which one clay mineral may be transformed into another. The latter topic will be further explored in Section 8.6.

8.4 STRUCTURAL CHARACTERISTICS OF NONSILICATE COLLOIDS

Iron and Aluminum Oxides

These clays consist of modified octahedral sheets with either iron (Fe^{3+}) or aluminum (Al^{3+}) in the cation positions. They have neither tetrahedral sheets nor silicon in their structures. Isomorphous substitution by ions of varying charge rarely occurs, so these clays do not have a large negative charge. The small amount of net charge these clays possess (positive and negative) is caused by the removal or addition of hydrogen ions at the surface oxy-hydroxyl groups. The presence of these bound oxygen and hydroxyl groups enables the surfaces of these clays to strongly adsorb and combine with anions such as phosphate or arsenate. The oxide clays are nonexpansive and generally exhibit relatively little stickiness, plasticity, and cation adsorption. They make quite stable materials for construction purposes (see Figure 3.44).

Gibbsite [$Al(OH)_3$], the most common soil aluminum oxide, is a prominent constituent of highly weathered soils (e.g., Oxisols and Ultisols). Figure 8.18 shows gibbsite to consist

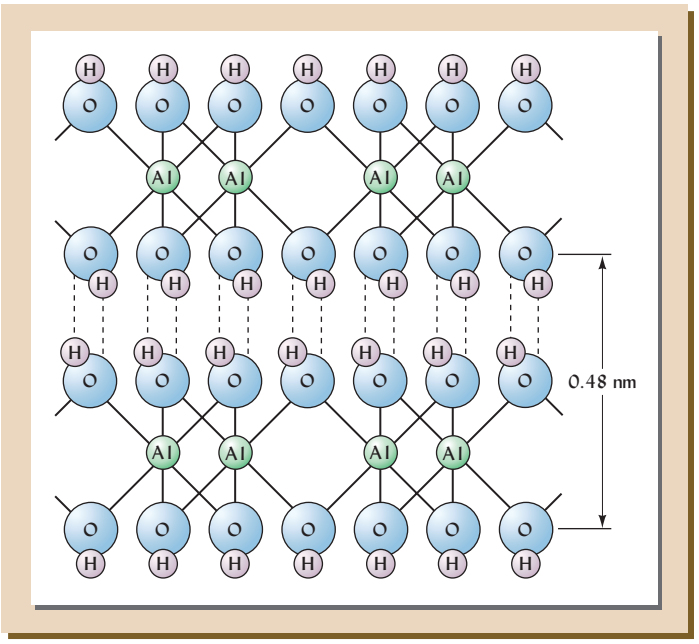

Figure 8.18 *A simplified diagram showing the structure of gibbsite, an aluminum oxide clay common in highly weathered soils. This clay consists of dioctahedral sheets (two are shown) that are hydrogen-bonded together. Other oxide-type clays have iron instead of aluminum in the octahedral positions, and their structures are somewhat less regular and crystalline than that shown for gibbsite. The surface plane of covalently bonded hydroxyls gives this, and similar clays, the capacity to strongly adsorb certain anions (see Section 8.8).*

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of a series of aluminum octahedral sheets linked to one another by hydrogen-bonding between their hydroxyls. Note that a plane of hydroxyls is exposed at the upper and lower surfaces of gibbsite crystals. These hydroxylated surfaces can strongly adsorb certain anions.

Other oxide-type clays have iron instead of aluminum in the central cation positions, and their octahedral structures are somewhat distorted and less regular than that of gibbsite. **Goethite** (FeOOH) and **ferrihydrite** ($Fe_2O_3 \cdot nH_2O$) are common iron oxide clays in temperate regions, accounting for the yellow-brown colors of many soils. **Hematite** (Fe_2O_3) is common in drier environments and gives redder colors to well-drained soils, especially in hot, dry climates (e.g., see Figure 4.2*c*).

In many soils, iron and aluminum oxide minerals are mixed with silicate clays. The oxides may form coatings on the external surfaces of the silicate clays, or they may occur as "islands" in the interlayer spaces of such 2:1 clays as vermiculites and smectites. In either case, the presence of iron and aluminum oxides can substantially alter the colloidal behavior of the associated silicate clays by masking charge sites, interfering with shrinkage and swelling, and providing anion-retentive surfaces.

Humus

As mentioned in Section 8.1, humus is comprised of noncrystalline heterogeneous organic substances whose chemical composition varies considerably, but generally contains 40–60% C, 30–50% O, 3–7% H, and 1–5% N. A small part of the humus in soils may consist of very large polymerized molecules of so-called humic acids with molecular weights in the 1000s of g/mol. The actual structures of these humic acids have not been identified and many soil chemists have concluded that most of the colloids in humus are comprised of tiny bits of partially decomposed or charred plant tissue, microbial cell walls and films of biomolecules closely associated with mineral colloids (Section 12.4). Many of the partially decomposed plant tissues and biomolecules contain many ring structures and carbon chains with chemically active groups of atoms that expose hydroxyl groups to the soil solution. Figure 8.19 provides a simplified diagram to illustrate the three main types of —OH groups thought to be responsible for the high amount of charge associated with these colloids. Negative or positive charges on the humus colloid develop as H^+ ions are either lost or gained by these groups. Both cations and anions are therefore attracted to and adsorbed by the humus colloid. The negative sites always outnumber the positive ones, and a very large *net* negative charge is associated with humus (Table 8.1). Because of its great surface area and many hydrophilic (water-loving) groups, humus can adsorb very large amounts of water per unit mass. However, humus also contains many hydrophobic sites and therefore can strongly adsorb a wide range of hydrophobic, nonpolar organic compounds (see Section 8.12). Because of its extraordinary influence on soil properties and behavior, we will delve much more deeply into the nature and function of soil organic matter in Section 12.4.

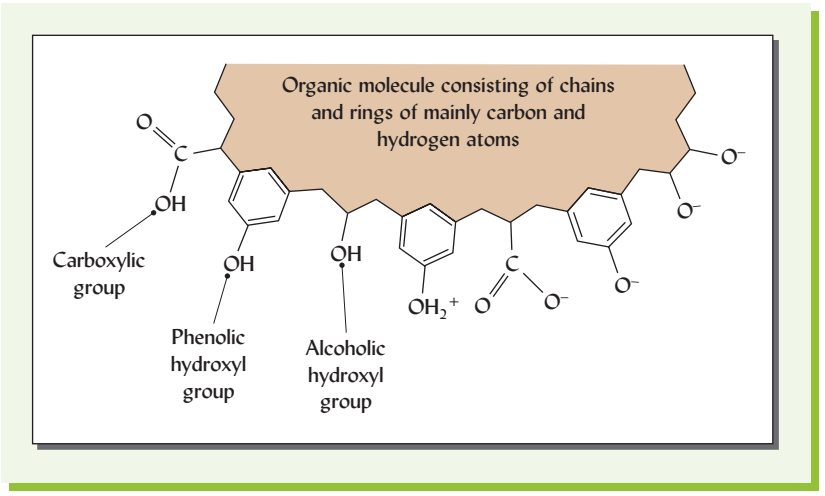

Figure 8.19 *A simplified diagram showing the principal chemical groups responsible for the high amount of negative charge on humus colloids. The three groups highlighted all include —OH that can lose its hydrogen ion by dissociation and thus become negatively charged. Note that the carboxylic, phenolic, and alcoholic groups on the right side of the diagram are shown in their disassociated state, while those on the left side still have their associated hydrogen ions. Note also that association with a second hydrogen ion causes a site to exhibit a net positive charge.* (Diagram courtesy of Ray R. Weil)

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8.5 GENESIS AND GEOGRAPHIC DISTRIBUTION OF SOIL COLLOIDS

Genesis of Colloids

The silicate clays develop from the weathering of a wide variety of minerals by at least two distinct processes: (1) a slight physical and chemical **alteration** of certain primary minerals, and (2) a **decomposition** of primary minerals with the subsequent **recrystallization** of certain of their products into the silicate clays. These processes will each be given brief consideration.

Alteration. The changes that occur as muscovite mica is altered to fine-grained mica represent a good example of alteration. Muscovite is a dioctahedral 2:1-type primary mineral with a nonexpanding crystal structure and a formula of $KAl_2(Si_3Al)O_{10}(OH)_2$. As weathering occurs, the mineral is broken down in size to the colloidal range. Part of the interlayer potassium is lost, and some silicon along with such cations as Ca^{2+} or Mg^{2+} are added from weathering solutions. The net result is a less rigid crystal structure and the availability of free electronegative charges at sites formerly occupied by the fixed interlayer potassium. The fine mica colloid that emerges still has a 2:1-type structure, having only been *altered* in the process.

Recrystallization. This process involves the complete breakdown of the crystal structure and recrystallization of clay minerals from products of this breakdown. It is the result of much more intense weathering than that required for the alteration process just described.

An example of recrystallization is the formation of kaolinite (a 1:1-type clay mineral). Kaolinite recrystallizes from solutions containing soluble aluminum and silicon from the breakdown of primary minerals with a 2:1-type structure. Such recrystallization makes possible the formation of more than one kind of clay from a given primary mineral. The specific clay mineral that forms depends on weathering conditions and the specific ions present in the weathering solution as crystallization occurs.

Relative Stages of Weathering. Specific conditions conducive to the formation of important clay types are shown in Figure 8.20. Note that fine-grained micas and magnesium-rich chlorites represent earlier weathering stages of the silicates, and kaolinite and (ultimately) iron and aluminum oxides the most advanced stages. The smectites (e.g., montmorillonite) represent intermediate stages. Different weathering stages may occur across climatic zones, landscapes or horizons within a single profile. As noted in Section 2.1, silicon tends to be lost as weathering progresses, leaving a lower Si:Al ratio in more highly weathered soil horizons.

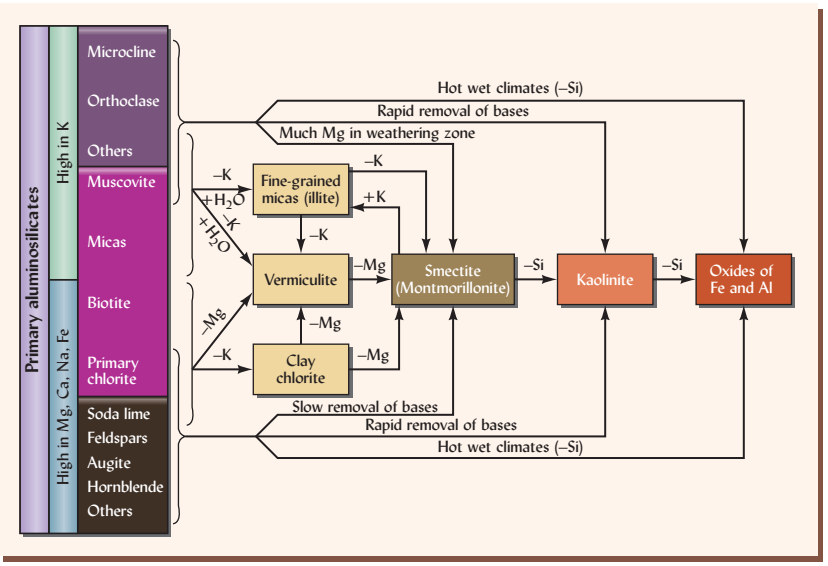

Figure 8.20 *Formation layer silicate clays and oxides of iron and aluminum. Fine-grained micas, chlorite, and vermiculite are formed through rather mild weathering of primary aluminosilicate minerals, whereas kaolinite and oxides of iron and aluminum are products of much more intense weathering. Intermediate weathering intensity favors smectite. In each case silicate clay genesis is accompanied by the removal in solution of such elements as Si, K, Na, Ca, and Mg. Several members of this weathering series may be present in a single soil profile, with the less weathered clay in the C horizon and the more weathered clay minerals in the B or A horizons.*

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Mixed and Interstratified Layers. In a given soil, it is common to find several silicate clay minerals in an intimate mixture. In fact, the properties and compositions of some mineral colloids are intermediate between those of the well-defined minerals described in Section 8.3. For example, a **mixed layer** or **interstratified** clay mineral in which some layers are more like mica and some more like vermiculite might be called *fine-grained mica-vermiculite.*

Iron and Aluminum Oxides. Iron oxides often are produced by the weathering of iron-containing primary silicate minerals or by precipitation of iron from soil solutions. Under aerated weathering conditions, divalent iron (Fe^{2+}) oxidizes rapidly to trivalent iron (Fe^{3+}), either while still within the structure of primary minerals or after its release into the soil solution. By reacting with oxygen atoms and water, the Fe^{3+} forms stable oxides and hydroxides (e.g., **goethite**, FeOOH and **hematite**, Fe_2O_3). Hematite is most characteristic of red soils formed under relatively dry, warm, well-oxidized conditions, but it can also be inherited from such soil parent materials as red shales. Other iron oxides precipitate under wet, poorly oxygenated conditions. Interestingly, certain highly weathered soils contain significant amounts of *maghematite*, a magnetic iron oxide that forms in surface horizons under the influence of the heat from brush fires. If a water suspension of such a soil is stirred with a magnetic stir-bar, this iron oxide can be readily observed as tiny particles clinging to the magnet.

Aluminum oxides, mainly **gibbsite** [$Al(OH)_3$], are produced by strong weathering environments in which acid leaching rapidly removes the Si released from the breakdown of primary and secondary silicate minerals. During weathering, hydrogen ions replace the K^+, Mg^{2+}, and other such ions in the crystal, causing the framework to break down and releasing the silicon and aluminum. The aluminum released by the breakdown of iron-rich rocks such as gabbro and basalt often forms gibbsite directly. The weathering of light-colored rocks such as granite and gneiss may first produce 1:1 silicate minerals such as kaolinite or halloysite, which yield gibbsite upon further weathering. Gibbsite is extremely stable in soils and typically represents the most advanced stage of weathering in soils.

Allophane and Imogolite. Relatively little is known of factors influencing the formation of allophane and imogolite. While they are commonly associated with materials of volcanic origin, they are also formed from igneous rocks and are found in some Spodosols. Apparently, volcanic ashes release significant quantities of $Si(OH)x$ and $Al(OH)x$ materials that precipitate as gels in a relatively short period of time. These minerals are generally poorly crystalline in nature, imogolite being the product of a more advanced state of weathering than that which produces allophane. Both types of minerals have a pronounced capacity to strongly retain anions as well as to bind with humus, protecting it from decomposition.

Humus. The growth of plants (especially their roots) and subsequent breakdown of plant residues by microorganisms and the concurrent stabilization of plant and microbial materials by protective interaction with other soil components and microenvironments results in the formation of the dark-colored, largely colloidal organic material called *humus* (see Section 12.4 for details), especially in soils high in adsorptive clay surfaces (such as Mollisols or Andisols) or low oxygen environments (such a Histosols). The various functional groups on the stabilized organic compounds provide charged sites for the attraction of both cations and anions.

Distribution of Clays by Geography and Soil Order

The clay of any particular soil is generally made up of a mixture of different colloidal minerals. In a given soil, the mixture may vary from horizon to horizon, because the kind of clay that develops depends not only on climatic influences and profile conditions but also on the nature of the parent material. The situation may be further complicated by the presence in the parent material itself of clays that were formed under a preceding and perhaps an entirely different type of climatic regime. Nevertheless, some broad generalizations are possible.

Table 8.3 shows the dominant clay minerals in different soil orders, descriptions of which were given in Chapter 3. The well-drained and highly weathered Oxisols and Ultisols of warm humid and subhumid tropics tend to be dominated by kaolinite, along with oxides of iron and aluminum. The smectite, vermiculite, and fine-grained mica groups are more prominent

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Table 8.3
PROMINENCE OF CLAY MINERALS IN DIFFERENT SOIL ORDERS AND TYPICAL ENVIRONMENTS FOR THESE SOILS

Soil order[a]	General weathering intensity	Typical location/ environment.	Fe, Al oxides	Kaolinite	Smectite	Fine-grained mica	Vermiculite	Chlorite	Intergrades
Aridisols	Low	Dry areas			XX	XX		X	X
Vertisols[b]	↑	Dry & wet seasons, warm, high Ca, Mg			XXX				X
Mollisols		Prairie, steppe		X	XX	X	X	X	X
Alfisols		Cool or semiarid forests		X	X	X	X	X	X
Spodosols		Boreal forests	X	X					
Ultisols	↓	Warm, wet forests	XX	XXX			X	X	X
Oxisols	High	Hot, wet tropics	XX	XXX					

[a]See Chapter 3 for soil descriptions.
[b]By definition these soils have swelling-type clays, which account for the dominance of smectites.

in Vertisols, Mollisols, and temperate region Alfisols where weathering is less intense. If the parent material is high in micas, fine-grained micas such as illite are apt to be formed. Parent materials that are high in metallic cations (particularly magnesium) or are subject to restricted drainage, which discourages the leaching of these cations, encourage smectite formation.

8.6 SOURCES OF CHARGES ON SOIL COLLOIDS

There are two major sources of charges on soil colloids: (1) the *permanent* charge imbalance brought about in some clay crystal structures by the isomorphous substitution of one cation by another of similar size but different charge, and (2) hydroxyls and other functional groups on the surfaces of the colloidal particles that may release or accept H^+ ions thus providing either negative or positive charges, *depending* on the solution pH.

Constant Charges on Silicate Clays

Since charges resulting from isomorphous substitution are not dependent on the pH, they are termed **permanent** or **constant charges**. Examples of specific substitutions will now be considered.

Negative Charges. A net negative charge is found in minerals where there has been an isomorphous substitution of a lower-charged ion (e.g., Mg^{2+}) for a higher-charged ion (e.g., Al^{3+}). Such substitution commonly occurs in aluminum-dominated dioctahedral sheets of smectite, vermiculite, and chlorite clay. As shown in Figure 8.5 (*right*), this leaves an unsatisfied negative charge.

A second example is the substitution of an Al^{3+} for an Si^{4+} in the tetrahedral sheet, which also leaves one unsatisfied negative charge from the tetrahedral oxygen atoms. Such a substitution is common in the fine-grained micas, vermiculites, and even some smectites.

Positive Charges. Isomorphous substitution can also be a source of positive charges if the substituting cation has a higher charge than the ion for which it substitutes. In a trioctahedral sheet, there are three magnesium ions surrounded by oxygen and hydroxy groups, and the

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sheet has no charge (review Figure 8.5). However, if an Al^{3+} ion substitutes for one of the Mg^{2+} ions, a positive charge results.

Such positive charges are characteristic of the trioctahedral hydroxide sheet in the interlayer of clay minerals such as chlorites, a charge that is overbalanced by negative charges in the tetrahedral sheet. Indeed, in several 2:1-type silicate clays, including chlorites and smectites, substitutions in both the tetrahedral and octahedral sheets can occur. The net charge in these clays is the balance between the negative and positive charges. In all 2:1-type silicate clays, however, the **net charge** is negative since those substitutions leading to negative charges far outweigh those producing positive charges (see Figure 8.21).

pH-Dependent Charges

Most of the charges associated with humus, 1:1-type clays, the oxides of iron and aluminum, and allophane are dependent on the soil pH and consequently is termed **variable** or **pH-dependent**. Both negative and positive charges come from this source.

Negative Charges. The pH-dependent charges are associated primarily with OH groups on the surfaces of the inorganic and organic colloids. Broken edges of mineral colloids also generate pH-dependent charges (see Figure 8.22). The OH groups or oxygen atoms are attached to iron and/or aluminum in the inorganic colloids (e.g., $>Al—OH$) and to the carbon in humus (e.g., $—C—OH$). Under moderately acid conditions, there is little or no charge on these particles, but as the pH increases, the hydrogen dissociates from the colloid OH group, and negative charges result

$$\underset{\substack{\text{No charge}\\\text{(soil solids)}}}{>Al—OH} + \underset{\text{(soil solution)}}{OH^-} \rightleftharpoons \underset{\substack{\text{Negative charge}\\\text{(soil solids)}}}{>Al—O^-} + \underset{\text{(soil solution)}}{H_2O} \tag{8.2}$$

As indicated by the $\rightleftharpoons$ arrows, such reactions are reversible. If the pH increases, more OH^- ions are available to force the reactions to the right, and the negative charge on the particle surfaces increases. If the pH is lowered, OH^- ion concentrations are reduced, the reaction goes back to the left, and the negative charge is reduced.

Another source of increased negative charges as the pH is increased is the removal of positively charged complex aluminum hydroxy ions [e.g., $Al(OH)_2{}^+$]. At low pH levels, these ions block negative sites on the silicate clays (e.g., vermiculite) and make them unavailable for cation exchange. As the pH is raised, the $Al(OH)_2{}^+$ ions react with the OH^- ion in the soil solution to form insoluble $Al(OH)_3$, thereby freeing the negatively charged sites

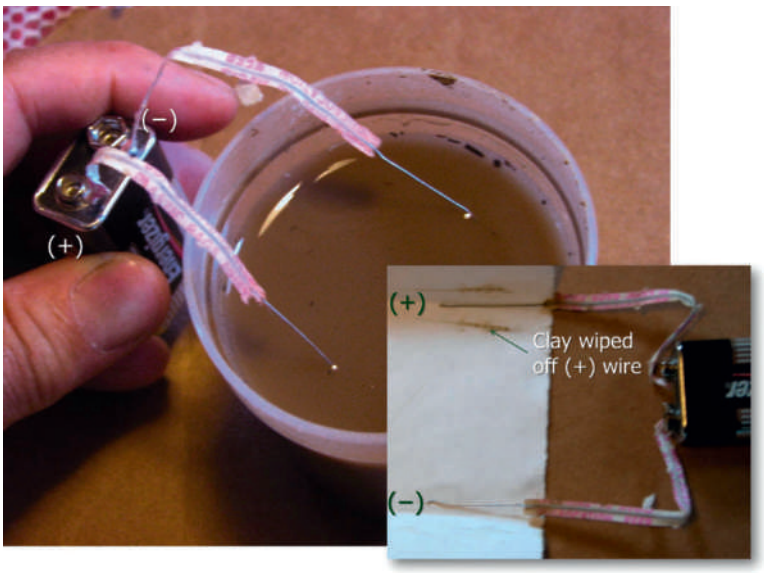

Figure 8.21 *Simple demonstration of the negatively charged nature of clay. Wires connected to the (–) and (+) terminals of a 9-volt battery are dipped for a few minutes in a suspension of clayey soil in water. The wires are then wiped on a piece of paper (inset), showing that the wire on the (+) terminal has attracted the clay while the (–) wire has not.* [Adapted from Weil (2015)]

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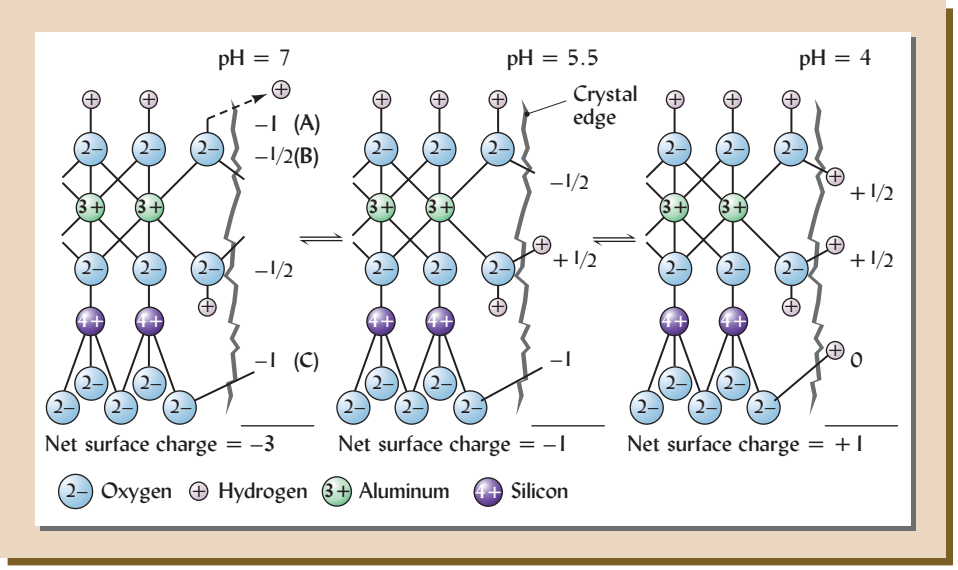

Figure 8.22 *How pH-dependent charges develop at the broken edge of a kaolinite crystal. Three sources of net negative surface charge at a high pH are illustrated* (left)*: (A) One (−1) charge from octahedral oxygen that has lost its H^+ ion by dissociation (the H broke away from the surface hydroxyl group and escaped into the soil solution). Note that such dissociation can generate negative charges all along the surface hydroxyl plane, not just at a broken edge. (B) One half (−1/2) charge from each octahedral oxygen that would normally be sharing its electrons with a second aluminum. (C) One (−1) charge from a tetrahedral oxygen atom that would normally be balanced by bonding to another silicon if it were not at the broken edge. The middle and right diagrams show the effect of acidification (lowering the pH), which increases the activity of H^+ ions in the soil solution. At the lowest pH shown (right), all of the edge oxygens have an associated H^+ ion, giving rise to a net positive charge on the crystal. These mechanisms of charge generation are similar to those illustrated for humus in Figure 8.19.* (Diagram courtesy of Ray R. Weil)

$$\begin{matrix} \diagdown \\ \diagdown \end{matrix}\!\!\mathrm{Al}\!-\!(\mathrm{OH})_2^- \ \mathrm{Al(OH)}_2^+ + \mathrm{OH}^- \longrightarrow \begin{matrix} \diagdown \\ \diagdown \end{matrix}\!\!\mathrm{Al}\!-\!(\mathrm{OH})_2^- + \mathrm{Al(OH)}_3 \qquad (8.3)$$

Negative charged site is blocked — Negative charge site is freed — No charge

Positive Charges. Under moderate to extreme acid soil conditions, humus, Fe, Al oxides, and some silicate clays may develop positive charges by **protonation**—the attachment of H^+ ions to the surface OH groups (Figure 8.22, *right*).

Since a mixture of humus and several inorganic colloids is usually found in soil, it is not surprising that positive and negative charges may be exhibited at the same time. In most soils of temperate regions, the negative charges far exceed the positive ones (Table 8.4). However, in some acid soils high in Fe, Al oxides, or allophane, the overall net charge may be positive. The effect of soil pH on positive and negative charges on such soils is illustrated in Figure 8.23.

The charge characteristics of selected soil colloids are shown in Table 8.4. Note the high percentage of constant negative charges in some 2:1-type clays (e.g., smectite and vermiculites). Humus, kaolinite, allophane and Fe, Al oxides have mostly variable (pH-dependent) negative charges and exhibit modest positive charges at low pH values. We will now turn our attention to how the charges on soil colloids facilitate the adsorption of oppositely charged ions from the soil solution.

8.7 ADSORPTION OF CATIONS AND ANIONS

In soil, the negative and positive surface charges on the colloids attract and hold a complex swarm of cations and anions. In Figure 8.1 ion adsorption was illustrated in a simplified manner, showing positive cations held on the negatively charged surfaces of a soil colloid. Actually, both cations and anions are usually attracted to the same colloid. In temperate-region soils, anions are commonly adsorbed in much smaller quantities than cations because these soils generally contain predominately 2:1-type silicate clays on which negative charges predominate. In the tropics, where soils are more highly weathered, acid, and rich in 1:1 clays and Fe, Al oxides, the amount of negative charge on the colloids is not so high, and positive charges are more abundant. Therefore, the adsorption of anions is more prominent in these soils.

Figure 8.24 shows how both cations and anions may be attracted to the same colloid if it has both positively and negatively charged sites. This figure also illustrates that adsorption of ions on colloidal surfaces occurs by the formation of two quite different general types of colloid–ion complexes referred to as *outer-sphere* and *inner-sphere* complexes.

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Table 8.4
CHARGE CHARACTERISTICS OF REPRESENTATIVE COLLOIDS SHOWING COMPARATIVE LEVELS OF PERMANENT (CONSTANT) AND pH-DEPENDENT NEGATIVE CHARGES AS WELL AS pH-DEPENDENT POSITIVE CHARGES

	Negative charge			
Colloid type	Total at pH 7, $cmol_c$ /kg	Constant, %	pH dependent, %	Positive charge, $cmol_c$/kg
Organic	200	10	90	0
Smectite	100	95	5	0
Vermiculite	150	95	5	0
Fine-grained micas	30	80	20	0
Chlorite	30	80	20	0
Kaolinite	8	5	95	2
Gibbsite (Al)	4	0	100	5
Goethite (Fe)	4	0	100	5
Allophane	30	10	90	15

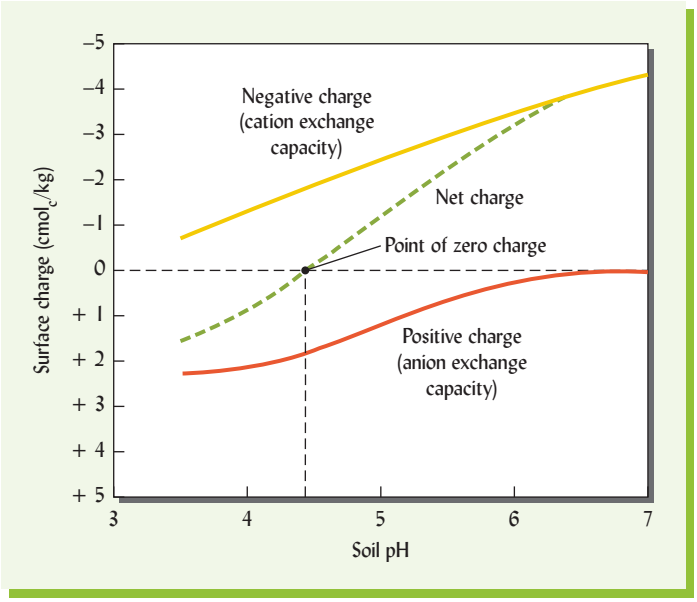

Figure 8.23 *Relationship between soil pH and positive and negative charges on an Oxisol surface horizon in Malaysia. The negative charges (cation exchange capacity) increase and the positive charges (anion exchange capacity) decrease with increasing soil pH. In the case illustrated, the positive and negative charges are in balance (zero net charge) at about pH 4.4.* [Redrawn from Shamshuddin and Ismail (1995)]

Outer- and Inner-Sphere Complexes

Remembering that water molecules surround (hydrate) cations and anions in the soil solution, we can visualize that in an **outer-sphere complex** water molecules form a bridge between the adsorbed ion and the charged colloid surface. Sometimes several layers of water molecules are involved. Thus, the ion itself never comes close enough to the colloid surface to form a bond with a specific charged site. Instead, the ion is only weakly held by electrostatic attraction, the charge on the oscillating hydrated ion balancing, in a general way, an excess charge of opposite sign on the colloid surface. Ions in an outer-sphere complex are therefore easily replaced by other similarly charged ions.

In contrast, adsorption via formation of an **inner-sphere complex** does *not* involve any intervening water molecules. Therefore, one or more direct bonds are formed between the adsorbed ion and the atoms in the colloid surface. One example already discussed is the case of

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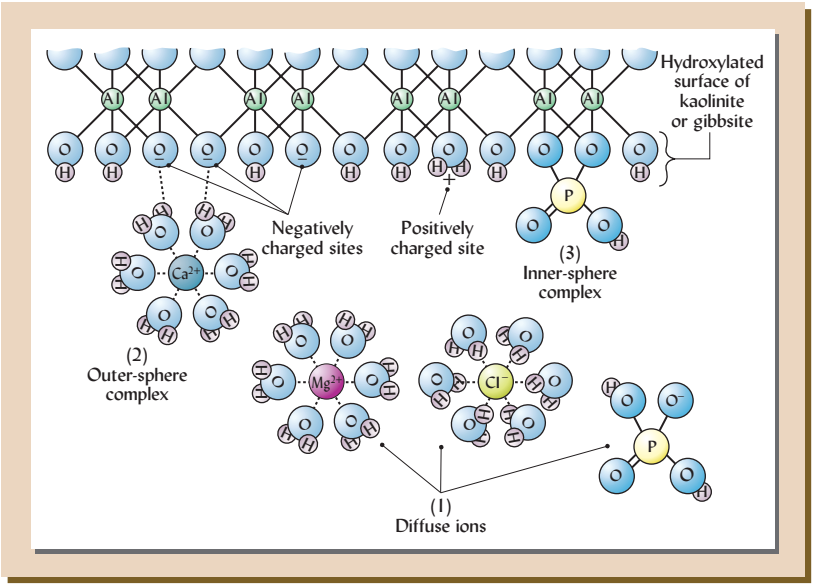

Figure 8.24 *Adsorption of ions on a colloid by the formation of outer-sphere and inner-sphere complexes. (1) Water molecules surround diffuse cations and anions (such as the Mg^{2+}, and Cl^- shown) in the soil solution. (2) In an outer-sphere complex (such as the adsorbed Ca^{2+} ion shown), water molecules form a bridge between the adsorbed cation and the charged colloid surface. (3) In the case of an inner-sphere complex (such as the adsorbed $H_2PO_4^-$ anion shown), no water molecules intervene, and the cation or anion binds directly with the metal atom (aluminum in this case) in the colloid structure. Outer-sphere complexes typify easily exchangeable ions that satisfy, in a general way, the net charge on the colloid surface. Inner-sphere complexes, on the other hand, are not easily replaced from the colloid surface, as they represent strong bonding of specific ions to specific sites on the colloid. Adsorption on an exposed hydroxylated surface octahedral sheet, such as that in kaolinite or gibbsite, is shown.* (Diagram courtesy of Ray R. Weil)

the K^+ ions that fit so snugly into the spaces between silicon tetrahedra in a mica crystal (see Figure 8.16). Since there are no intervening water molecules, the K^+ ions are directly bonded by sharing electrons with the negatively charged tetrahedral oxygen atoms. Similarly, strong inner-sphere complexes may be formed by reactions of Cu^{2+} or Ni^{2+} with the oxygen atoms in silica tetrahedra.

Another important example, this time involving an anion, occurs when a $H_2PO_4^+$ ion is directly bonded by shared electrons with the octahedral aluminum in the colloid structure (Figure 8.24). Other ions cannot easily replace an ion held in an inner-sphere complex because this type of adsorption involves relatively strong bonds that are dependent on the compatible nature of specific ions and specific sites on the colloid.

Figure 8.24 illustrates only two examples of adsorption complexes on one type of colloid. In other colloids, charged silica tetrahedral surfaces form inner- and outer-sphere complexes by mechanisms similar to those shown in the figure. Permanent charges from isomorphous substitution in the interior structure of a colloid (not shown in Figure 8.24) can also cause adsorption of outer-sphere complexes.

Table 8.5 lists cations and anions commonly adsorbed by inner and outer sphere complexation. The adsorption of these ions by soil colloids greatly affects their mobility and biological availability, thereby influencing both soil fertility and environmental quality. Note that the soil solution and colloidal surfaces in most soils are dominated mainly by just a few of the cations and anions, the others being found in much smaller amounts or only in special situations such as contaminated soils.

8.8 CATION EXCHANGE REACTIONS

The phenomenon of cation exchange in soils was stumbled upon in 1840s England by two farmers and then further investigated by J. Thomas Way, a consulting agricultural chemist (Way, 1850). They poured smelly brown cow urine and other solutions containing *ammonium* onto columns of soil. To their surprise, the liquid "went in manure and came out water." The water draining out from the bottom of the column was not smelly or colored and did not contain ammonium, but instead was clear and contained mainly *calcium*. Apparently the ammonium (NH_4^+) had exchanged places with the calcium (Ca^{2+}).

To understand what was happening, let us consider the case of an outer-sphere complex between a negatively charged colloid surface and a hydrated cation (such as the Ca^{2+}, Mg^{2+}, and K^+ ions shown in Figures 8.24 and 8.25). Such an outer-sphere complex is only loosely held

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Table 8.5
CATIONS AND ANIONS COMMONLY ADSORBED TO SOIL COLLOIDS AND IMPORTANT IN PLANT NUTRITION AND ENVIRONMENTAL QUALITY
The listed ions form inner- and/or outer-sphere complexes with soil colloids. Ions marked by an asterisk (*) are among those that predominate in most soil solutions. Many other ions may be important in certain situations.

Cation	Formula	Comments	Anion	Formula	Comments
Ammonium	NH_4^+	Plant nutrient	Arsenate	AsO_4^{3-}	Toxic to animals
Aluminum	Al^{3+}, $AlOH^{2+}$, $Al(OH)_2^+$	Toxic to many plants	Borate	$B(OH)_4^-$	Plant nutrient, can be toxic
Calcium*	Ca^{2+}	Plant nutrient	Bicarbonate	HCO_3^-	Toxic in high-pH soils
Cadmium	Cd^{2+}	Toxic pollutant	Carbonate*	CO_3^{2-}	Forms weak acid
Cesium	Cs^+	Radioactive contaminant	Chromate	CrO_4^{2-}	Toxic pollutant
Copper	Cu^{2+}	Plant nutrient, toxic pollutant	Chloride*	Cl^-	Plant nutrient, toxic in large amounts
Hydrogen*	H^+	Causes acidity	Fluoride	Fl^-	Toxic, natural, and pollutant
Iron	Fe^{2+}	Plant nutrient	Hydroxyl*	OH^-	Alkalinity factor
Lead	Pb^{2+}	Toxic to animals, plants	Nitrate*	NO_3^-	Plant nutrient, pollutant in water
Magnesium*	Mg^{2+}	Plant nutrient	Molybdate	MoO_4^{2-}	Plant nutrient, can be toxic
Manganese	Mn^{2+}	Plant nutrient	Phosphate	HPO_4^{2-}	Plant nutrient, water pollutant
Nickel	Ni^{2+}	Plant nutrient, toxic pollutant	Selenate	SeO_4^{2-}	Animal nutrient and toxic pollutant
Potassium*	K^+	Plant nutrient	Selenite	SeO_3^{2-}	Animal nutrient and toxic pollutant
Sodium*	Na^+	Used by animals, some plants, can damage soil	Silicate*	SiO_4^{4-}	Mineral weathering product, used by plants
Strontium	Sr^{2+}	Radioactive contaminant	Sulfate*	SO_4^{2-}	Plant nutrient
Zinc	Zn^{2+}	Plant nutrient, toxic pollutant	Sulfide	S^{2-}	In anaerobic soils, forms acid on oxidation

together by electrostatic attraction, and the adsorbed ions remain in constant motion near the colloid surface. There are moments (microseconds) when an adsorbed cation may vibrate out a bit farther than usual from the colloid surface. Such a moment provides an opportunity for another hydrated cation from the soil solution (say a copper Cu^{2+} ion as shown in Figure 8.25) to diffuse into a position a bit closer to the negative site on the colloid. The instant this should occur, the second ion would replace the formerly adsorbed ion—freeing the latter to diffuse out into the soil solution. In this manner, an *exchange of cations* between the adsorbed and diffuse state takes place. If water is percolating through the soil profile, cations applied to the surface of a soil (such as the Cu^{2+} from copper sulfate in Figure 8.25) may be adsorbed and retained in the upper soil horizons by exchanging with some of the cations originally adsorbed on the colloids there (such as the Ca^{2+} ions shown in Figure 8.25). As a result, water draining from the profile contains ions desorbed from the soil instead of the ions applied to the surface. The degree to which such processes occur can have important implications for the movement of contaminants from land to water and of nutrients from soils to plant roots.

The process just described is referred to as **cation exchange** (see also Section 8.1). If a hydrated *anion* similarly replaces another hydrated anion at a *positively* charged colloid site, the process is termed **anion exchange**. The ions held in outer-sphere complexes from which they can be replaced by such exchange reactions are said to be **exchangeable** cations or anions. As a group, all the colloids in a soil, inorganic and organic, capable of holding exchangeable cations or anions are termed the cation or anion **exchangeable complex**.

Principles Governing Cation Exchange Reactions

Figure 8.25 is a very simplified visualization of cation exchange. In fact, if we are to have a more sophisticated understanding of exchange reactions and the roles they play, we will need to become aware of a number of principles that govern how these reactions take place.

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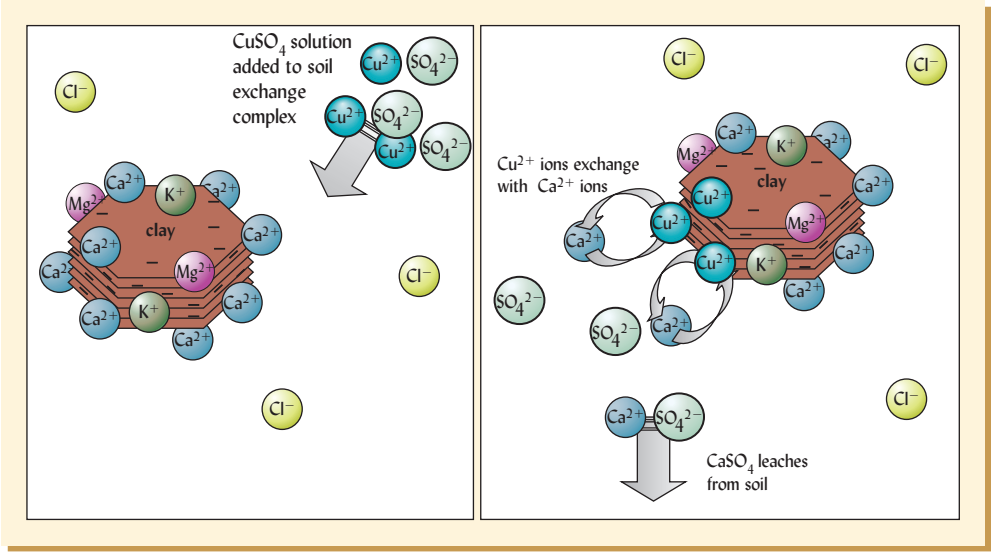

Figure 8.25 *A highly simplified visualization of cation exchange in soils. Negatively charged clay particles attract a gyrating swarm of positively charged ions. These ions form weak outer-sphere complexes with the clay and are known as exchangeable ions. In most soils Ca^{2+}, Mg^{2+}, and K^{+} make up the majority of exchangeable ions.* (Left) *A chemical compound is added to the soil; in this example copper sulfate from a fungicide spray. The Cu^{2+} cations migrate toward the negatively charged clay particle. As the exchangeable ions vibrate within their outer-sphere complex with the clay, the Cu^{2+} ions in the solution are also in constant motion nearby.* (Right) *Occasionally an exchangeable Ca^{2+} ion vibrates to the outer edge of the clay's attractive charge field at the same instant that a Cu^{2+} ion gyrates into the attractive field such that the Cu^{2+} becomes captured by the negative charge while the Ca^{2+} is freed to diffuse away from the clay in the soil solution. Thus the two ions have exchanged places. Meanwhile, anions such as the sulfate SO_4^{2-} ions are repelled by the negatively charged clay. The Ca^{2+} freed into the solution by exchange with the Cu^{2+} soon pairs up with a SO_4^{2-} anion and may leach down through the soil profile with percolating water as copper sulfate* (lower right). *A scientist making observations on this soil system might note that copper went in the top but calcium came out the bottom.* (Diagram courtesy of Ray R. Weil)

Reversibility. We can illustrate the process of cation exchange using a simple reaction in which a hydrogen ion (perhaps generated by organic matter decomposition—see Section 9.1) displaces a sodium ion from its adsorbed state on a colloid surface:

$$\boxed{\text{Colloid}}\ Na^+ + \underset{\text{(soil solution)}}{H^+} \rightleftharpoons \boxed{\text{Colloid}}\ H^+ + \underset{\text{(soil solution)}}{Na^+} \tag{8.4}$$

The reaction takes place rapidly and, as shown by the double arrows, the reaction is reversible. It will go to the left if sodium is added to the system. This reversibility is a fundamental principle of cation exchange.

Charge Equivalence. Another basic principle of cation exchange reactions is that the exchange takes place on a *charge-for-charge* basis. Therefore, although one H^+ ion exchanged with *one* Na^+ ion in the reaction just shown, it would require *two* singly charged H^+ ions to exchange with *one* divalent Ca^{2+} ion. If the reaction is reversed, one Ca^{2+} ion will displace two H^+ ions. In other words, two charges from one cation species replace two charges from the other:

$$\boxed{\text{Colloid}}\ Ca^{2+} + \underset{\text{(soil solution)}}{2\,H^+} \rightleftharpoons \boxed{\text{Colloid}}\ \begin{matrix}H^+\\H^+\end{matrix} + \underset{\text{(soil solution)}}{Ca^{2+}} \tag{8.5}$$

Note that by this principle, it would require three Na^+ ions to replace a single Al^{3+} ion, and so on.

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Ratio Law. Consider an exchange reaction between two similar cations, say Ca^{2+} and Mg^{2+}. If there are many Ca^{2+} ions adsorbed on a colloid and some Mg^{2+} is added to the soil solution, the added Mg^{2+} ions will begin displacing the Ca^{2+} from the colloid. This will bring more Ca^{2+} into the soil solution and these Ca^{2+} ions will, in turn, displace some of the Mg^{2+} back off the colloid. Theoretically, these exchanges will continue back and forth until equilibrium is reached. At this point, there will be no further *net* change in the number of adsorbed Ca^{2+} and Mg^{2+} ions (although the exchanges will continue each balancing the other). The **ratio law** tells us that, at equilibrium, the ratio of Ca^{2+} to Mg^{2+} on the colloid will be the same as the ratio of Ca^{2+} to Mg^{2+} in the solution and both will be the same as the ratio in the overall system. To illustrate this concept, assume that 20 Ca^{2+} ions are initially adsorbed on a soil colloid and either 5 or 80 Mg^{2+} ions are added to the system:

$$\boxed{\text{Colloid}}\ 20\ Ca^{2+} + \underset{\text{(soil solution)}}{5\ Mg^{2+}} \rightleftharpoons \boxed{\text{Colloid}} \begin{matrix} 16\ Ca^{2+} \\ 4\ Mg^{2+} \end{matrix} + \underset{\text{(soil solution)}}{1\ Mg^{2+} + 4\ Ca^{2+}} \qquad \text{Ratio: 4 Ca:1 Mg} \tag{8.6}$$

$$\boxed{\text{Colloid}}\ 20\ Ca^{2+} + \underset{\text{(soil solution)}}{80\ Mg^{2+}} \rightleftharpoons \boxed{\text{Colloid}} \begin{matrix} 4\ Ca^{2+} \\ 16\ Mg^{2+} \end{matrix} + \underset{\text{(soil solution)}}{64\ Mg^{2+} + 16\ Ca^{2+}} \qquad \text{Ratio: 1 Ca:4 Mg} \tag{8.7}$$

If the two exchanging ions are not of the same charge (e.g., K^+ exchanging with Mg^{2+}), the reaction becomes somewhat more complicated and a modified version of the ratio law would apply. We will not go into any more detail on this point, except to note that the reactions just given suggest that in order to completely replace one element with a second element by cation exchange, an overwhelming amount of the second ion must be added. This fact must be considered when using displacement to measure the amounts of exchangeable ions or exchange sites in soils (see Section 8.9).

Up to this point, our discussion of exchange reactions has assumed that both ionic species (elements) exchanging places take part in the exchange reaction in exactly the same way. This assumption must be modified to take into account three additional factors if we are to understand how exchange reactions actually proceed in nature.

Anion Effects on Mass Action. In the reactions just discussed, we have not mentioned the anions that always accompany cations in solution. We also showed the exchange reactions as being completely reversible, with an equal chance of proceeding to the right or the left. In reality, the laws of **mass action** tell us that an exchange reaction will be more likely to proceed to the right if the released ion is prevented from reacting in the reverse direction. This may be accomplished if the released cation on the right side of the reaction either *precipitates*, *volatilizes*, or *strongly associates* with an anion. In each case, most of the displaced cations will be removed from solution and so will not be able to reverse the exchange. To illustrate this concept, consider the displacement of H^+ ions on an acid colloid by Ca^{2+} ions added to the soil solution, either as calcium chloride or as calcium carbonate:

$$\boxed{\text{Colloid}} \begin{matrix} H^+ \\ H^+ \end{matrix} + \underset{\text{(added)}}{CaCl_2} \rightleftharpoons \boxed{\text{Colloid}}\ Ca^{2+} + \underset{\text{(dissociated ions)}}{2\ H^+ + 2\ Cl^-} \tag{8.8}$$

$$\boxed{\text{Colloid}} \begin{matrix} H^+ \\ H^+ \end{matrix} + \underset{\text{(added)}}{CaCO_3} \rightleftharpoons \boxed{\text{Colloid}}\ Ca^{2+} + \underset{\text{Water}}{H_2O} + \underset{\text{(gas)}}{CO_2\uparrow} \tag{8.9}$$

In the first reaction, $CaCl_2$ is added, but relatively little calcium will end up on the colloid because the displaced hydrogen ions remain active in the solution and can reverse the reaction, thus displacing calcium back off the colloid. In the second reaction, where $CaCO_3$ is added, when a hydrogen ion is displaced off the colloid, it combines with an oxygen atom from the $CaCO_3$ to form water. Furthermore, the CO_2 produced is a gas, which

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can volatilize out of the solution and leave the system. The removal of these products pulls the reaction to the right. Therefore, much more Ca will be adsorbed on the colloid and much more H displaced if $CaCO_3$, rather than an equivalent amount of $CaCl_2$, is added to the hydrogen-dominated soil. This principle helps explain why $CaCO_3$ (in the form of limestone) is effective in neutralizing an acid soil, while calcium chloride is not (see Section 9.11).

Cation Selectivity. Up to now, we have assumed that both cation species taking part in the exchange reaction are held with equal tenacity by the colloid and therefore have an equal chance of displacing each other. In reality, some cations are held much more tightly than others and so are less likely to be displaced from the colloid. In general, the higher the charge and the smaller the hydrated radius of the cation, the more strongly it will adsorb to the colloid. Because exchangeable adsorption involves creation of an outer-sphere complex, it is the ion's hydrated radius, not the ionic radius, that affects the strength of adsorption. For example, Na^+ is very weakly held because, while it has a relatively small ionic radius (Table 8.2), it carries a large shell of water, giving it a relatively large hydrated radius of 79 nm (Table 8.6). The order of strength of adsorption for selected cations is:

$$Al^{3+} > Sr^{2+} > Ca^{2+} > Mg^{2+} > Cs^+ > K^+ = NH_4^+ > Na^+ > Li^+$$

The less tightly held cations oscillate farther from the colloid surface and therefore are the most likely to be displaced into the soil solution and carried away by leaching. This series therefore explains why the soil colloids are dominated by Al^{3+} (and other aluminum ions) and Ca^{2+} in humid regions and by Ca^{2+} in drier regions, even though the weathering of minerals in many parent materials provides relatively larger amounts of K^+, Mg^{2+}, and Na^+ (see Section 8.10). The strength of adsorption of the H^+ ion is difficult to determine because hydrogen-dominated mineral colloids break down to form aluminum-saturated colloids.

The relative strengths of adsorption order may be altered on certain colloids whose properties favor adsorption of particular cations. An important example of such colloidal "preference" for specific cations is the very high affinity for K^+ ions (and the similarly sized NH_4^+ and Cs^+ ions) exhibited by vermiculite and fine-grained micas, which attract these ions to intertetrahedral spaces exposed at weathered crystal edges (Section 8.3). The influence of

Table 8.6
SOME EXCHANGEABLE IONS, THEIR HYDRATED SIZE, AND THEIR EXPECTED REPLACEMENT BY NH_4^+ IONS
Among ions of a given charge, the larger the hydrated radius, the more easily it is replaced.

Element	Ion	Hydrated ionic radius,[a] nm	Likely replacement of ion initially saturating a kaolinite clay if $cmol_c$ NH_4^+ added = CEC of the soil,[b] %
Lithium	Li^+	1.00	80
Sodium	Na^+	0.79	67
Ammonium	NH_4^+	0.54	50
Potassium	K^+	0.53	49
Rubidium	Rb^+	0.51	48
Cesium	Cs^+	0.50	47
Magnesium	Mg^{2+}	1.08	31
Calcium	Ca^{2+}	0.96	29
Strontium	Sr^{2+}	0.96	29
Barium	Ba^{2+}	0.88	26

[a]Not to be confused with nonhydrated radii (Table 8.2), hydrated radii are from Evangelou and Phillips (2005).
[b]Based on empirical data from various sources and assumes no special affinity by kaolinite for any of the listed ions.

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different colloids on the adsorption of specific cations impacts the availability of cations for leaching or plant uptake (see Section 14.15 and Box 8.4). Certain metals such as copper, mercury, and lead have very high selective affinities for sites on humus and iron oxide colloids, making most soils quite efficient at removing these potential pollutants from water leaching through the profile.

Complementary Cations. In soils, colloids are always surrounded by many different adsorbed cation species. The likelihood that a given adsorbed cation will be displaced from a colloid is influenced by how strongly its neighboring cations (sometimes called **complementary ions**) are adsorbed to the colloid surface. For example, consider an adsorbed Mg^{2+} ion. An ion diffusing in from the soil solution is more likely to displace one of the

BOX 8.4

CATION EXCHANGE AND FOOD CONTAMINATION BY NUCLEAR FALLOUT

A nuclear accident can contaminate the environment with radioactive isotopes such as cesium (^{137}Cs) and strontium (^{90}Sr) that readily move into the food chain because of their chemical similarity to K and Ca, respectively (see periodic table in Appendix B). If taken into the body, the radiation released by these radioisotopes causes a high incidence of cancer. Contamination of soil with radioisotopes can lead to their uptake by agricultural crops and hence the contamination of human food supplies (see Section 18.11). The 1986 meltdown of a nuclear power plant in Chernobyl spewed about 7 tons of radioactive material, contaminating millions of hectares of land, including some 4 million hectares in Europe outside the immediate area in Belarus, Ukraine, and Russia. World health experts estimate that this radiation may cause between 4000 and 60,000 people to die of cancer. In the event of such widespread soil contamination, safeguarding the food supply requires the ability to predict which soils are likely to produce contaminated vegetables, cattle fodder, and dairy products. One obvious factor to consider is the amount of radioactive contamination in a soil. However, the ratio of ^{137}Cs in the soil to ^{137}Cs in plants varies by four orders of magnitude from one soil to another. In other words, even if two soils have the same ^{137}Cs concentration, the food produced on one soil may be 10,000 times more ^{137}Cs-contaminated than that produced on the other soil. This is because ^{137}Cs availability for plant uptake is largely governed by cation exchange reactions in the soil. If the soil has little capacity to adsorb cations, most of the ^{137}Cs will remain in the soil solution, where roots will easily take it up. Soils with more clay and humus will adsorb much of the ^{137}Cs, releasing into the soil solution such previously adsorbed cations as K^+ and Ca^{2+}.

A study in Belgium found that the risk of ^{137}Cs uptake by plants was closely related to soil clay content in northern Belgium, but only weakly related in southern Belgium (see Figure 8.26). Differences in the types of clays present in soils from each region explain this finding. Apparently, in northern Belgium (but not in southern Belgium), soils are dominated by dioctahedral fine-grained mica and vermiculite, both minerals that exhibit a high selectivity for the K^+ (as well as for the similarly sized NH_4^+ and Cs^+) ions that fit so well into their interlayer spaces. The $^{137}Cs^+$ ions in the soil solution preferentially displace Ca^{2+} and other ions from the colloids. These soils are therefore capable of "intercepting" most of the $^{137}Cs^+$ before plants can take it up. However, because K^+ ions are equally attracted to these clays, repeated additions of potassium fertilizer to these soils would release much of the adsorbed $^{137}Cs^+$ by cation exchange, making it available again for plant uptake.

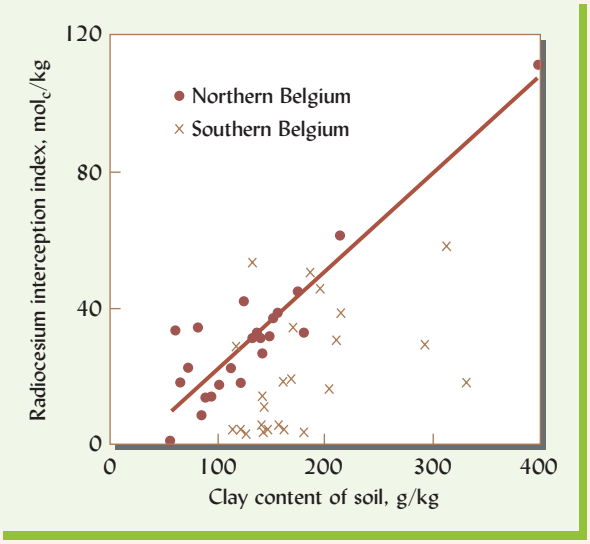

Figure 8.26 *Influence of clay content on the Radiocesium Interception Index—the ability of soils to reduce plant uptake of radioactive cesium. The soils were sampled in pastures used to feed dairy cows and produce milk in southern (×) and northern (•) Belgium. In southern Belgium, little relationship existed between the index and the soil clay contents. However, a strong relationship existed in the north, where micaceous parent materials are common and soils are dominated by dioctahedral fine-grained mica and vermiculite clays.* [Redrawn from data in Waegeneers et al. (1999)]

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neighboring ions rather than the Mg^{2+} ion, if the neighboring adsorbed ions are loosely held. If they are tightly held, then the chances are greater that the Mg^{2+} ion will be displaced. The influence of complementary ions on the availability of nutrient cations for plant uptake will be discussed in Section 8.10.

Integrated Example. In soils, cation exchange reactions follow the basic principles just illustrated. However, because there are many different cations, both adsorbed on the cation exchange complex and free in the soil solution, the overall reactions are much more complicated than the simple two-species interactions we have discussed so far. The following example illustrates the combined influence of charge equivalence, ion selectivity, and complementary ions in cation exchange

$$\boxed{\text{Colloid}}\begin{matrix}20\ Ca^{2+}\\5\ K^{+}\\10\ Mg^{2+}\\3\ Na^{+}\\10\ Al^{3+}\end{matrix} + 20\ NH_4^{+} + 20\ Cl^{-} \rightleftharpoons \boxed{\text{Colloid}}\begin{matrix}19\ Ca^{2+}\\1\ K^{+}\\8\ Mg^{2+}\\13\ NH_4^{+}\\10\ Al^{3+}\end{matrix} + 4\ K^{+} + 3\ Na^{+} + 2\ Mg^{2+} + Ca^{2+} + 7\ NH_4^{+} + 20\ Cl^{-} \qquad (8.10)$$

Note that 13 charges from NH_4^+ displaced a total of 13 charges from the initially adsorbed cations. Also note that a much larger proportion of loosely held Na^+, K^+, and Mg^{2+} were exchanged rather than the more tightly held Al^{3+} and Ca^{2+}. *If* more of the complementary ions had been Al^{3+}, then more of the Ca^{2+} would have been displaced and released to the soil solution, where it would have been easily leached or taken up by plants. Although the example merely approximates the ratio law, it does show that only a portion of the added NH_4^+ ions were adsorbed. Leaching loss of the adsorbed NH_4^+ ions would be retarded, but they could still serve as a source of nitrogen for plant roots by further exchange reactions.

8.9 CATION EXCHANGE CAPACITY (CEC)

Previous sections have dealt qualitatively with exchange reactions. We now turn to a consideration of the quantitative CEC. This property is defined simply as the sum total of the exchangeable cationic charges that a soil can absorb.

Means of Expression

The CEC is expressed as the number of moles of positive charge adsorbed per unit mass. In order to be able to deal with whole numbers of a convenient size, many publications, including this textbook, report CEC values in centimoles of charge per kilogram ($cmol_c$/kg). Some publications still use the older unit, milliequivalents per 100 grams (me/100 g), which gives the same value as $cmol_c$/kg (1 me/100 g = 1 $cmol_c$/kg). A particular soil may have a CEC of 15 $cmol_c$/kg, indicating that 1 kg of the soil can hold 15 $cmol_c$ of H^+ ions, for example, and can exchange this number of charges from H^+ ions for the same number of charges from any other cation. This means of expression emphasizes that exchange reactions take place on a charge-for-charge (not an ion-for-ion) basis. The concept of a mole of charges and its use in CEC calculations are reviewed in Box 8.5.

Methods of Determining CEC

The CEC is an important soil chemical property that is used for classifying soils in *Soil Taxonomy* (e.g., in defining an Oxic, Mollic, or Kandic diagnostic horizon, Section 3.2) and for assessing their fertility and environmental behavior. Several different standard methods can be used to determine the CEC of a soil. In general, a concentrated solution of a particular exchanger cation (e.g., Ba^{2+}, NH_4^+, or Sr^{2+}) is used to leach the soil sample. This provides an overwhelming number of the exchanger cations that can completely replace all the exchangeable cations initially in the soil. Then, the CEC can be determined by measuring either the

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BOX 8.5

CHEMICAL EXPRESSION OF CATION EXCHANGE

One mole of any atom, molecule, or charge is defined as 6.02×10^{23} (Avogadro's number) of atoms, molecules, or charges. Thus, 6.02×10^{23} negative charges associated with the soil colloidal complex would attract 1 mole of positive charge from adsorbed cations such as Ca^{2+}, Mg^{2+}, and H^+. The number of moles of the positive charge provided by the adsorbed cations in any soil gives us a measure of the CEC of that soil.

The CEC of soils commonly varies from 0.03 to 0.5 mole of positive charge per kilogram (mol_c/kg). Expressing this same range of CEC values in centimoles (1/100s of a mole) gives convenient whole numbers: 3–50 $cmol_c$/kg.

CALCULATING MASS FROM MOLES

Using the mole concept, it is easy to relate the moles of charge to the mass of ions or compounds involved in cation or anion exchange. Consider, for example, the exchange that takes place when adsorbed sodium ions in an alkaline arid-region soil are replaced by hydrogen ions:

$$\boxed{\text{Colloid}}\ Na^+ + H^+ \rightleftharpoons \boxed{\text{Colloid}}\ H^+ + Na^+$$

If 1 $cmol_c$ of adsorbed Na^+ ions per kilogram of soil were replaced by H^+ ions in this reaction, how many grams of Na^+ ions would be replaced?

Since the Na^+ ion is singly charged, the mass of Na^+ needed to provide 1 mole of charge (1 mol_c) is the gram atomic weight of sodium, or 23 g (see periodic table in Appendix B). The mass providing 1 *centimole* of charge ($cmol_c$) is 1/100 of this amount; thus, the mass of the 1 $cmol_c$ Na^+ replaced is 0.23 g Na^+/kg soil. The 0.23 g Na^+ would be replaced by only 0.01 g H, which is the mass of 1 $cmol_c$ of this much lighter element.

Another example is the replacement of H^+ ions when hydrated lime [$Ca(OH)_2$] is added to an acid soil. This time assume that 2 $cmol_c$ H^+/kg soil is replaced by the $Ca(OH)_2$, which reacts with the acid soil as follows:

$$\boxed{\text{Colloid}}\ \begin{matrix} H^+ \\ H^+ \end{matrix} + Ca(OH)_2 \rightleftharpoons \boxed{\text{Colloid}}\ Ca^{2+} + 2H_2O$$

Since the Ca^{2+} ion in each molecule of $Ca(OH)_2$ has two positive charges, the mass of $Ca(OH)_2$ needed to replace 1 mole of charge from the H^+ ions is only one-half of the gram molecular weight of this compound, or 74/2 = 37 g. A comparable figure for 1 centimole is 37/100, or 0.37 grams. The mass of $Ca(OH)_2$ needed to replace 2 $cmol_c$ H^+/kg soil is:

$$2\ cmol_c\ Ca(OH)_2/kg \times 0.37\ g\ Ca(OH)_2/cmol_c$$
$$= 0.74\ g\ Ca(OH)_2/kg\ soil$$

The 0.74 g $Ca(OH)_2$/kg soil can be converted to the amount of $Ca(OH)_2$ needed to replace 2 $cmol_c$ H^+/kg from the surface 15 cm of soil in a 1 ha field, remembering from Chapter 4 (Section 4.7, footnote 11) that this depth of soil typically weighs 2 million kg/ha

$$0.74\ g/kg \times 2 \times 10^6\ kg = 1.48 \times 10^6\ g$$
$$= 1.48 \times 10^3\ kg = 1.48\ Mg$$

CHARGE AND CHEMICAL EQUIVALENCY

In each preceding example, the number of charges provided by the replacing ion is equivalent to the number associated with the ion being replaced. Thus, 1 mole of negative charges attracts 1 mole of positive charges whether the charges come from H^+, K^+, Na^+, NH_4^+, Ca^{2+}, Mg^{2+}, Al^{3+}, or any other cation. Keep in mind, however, that only one-half the atomic weights of divalent cations, such as Ca^{2+} or Mg^{2+}, and only one-third the atomic weight of trivalent Al^{3+} are needed to provide 1 mole of charge. This *chemical equivalency* principle applies to both cation and anion exchange.

number of exchanger cations adsorbed (Figure 8.27*d*) or the amounts of each of the displaced elements originally held on the exchange complex (usually Ca^{2+}, Al^{3+}, Mg^{2+}, K^+, and Na^+, Figure 8.27*b*). See Box for detailed calculations.

Buffer CEC Methods. The CEC procedure often calls for use of a solution buffered to maintain a certain pH (usually either pH 7.0 using ammonium as the exchanger cation or pH 8.2 using barium as the exchanger cation). If the native soil pH is less than the pH of the buffered solution, then these methods measure not only the cation exchange sites active at the pH of the particular soil, but also any pH-dependent exchange sites (see Section 8.6) that *would* become negatively charged *if* the soil pH were raised to pH 7.0 or 8.2. Thus these methods exaggerate the true CEC of acid soils.

Effective CEC (Unbuffered). An alternative CEC procedure uses unbuffered solutions to allow the exchange to take place at the actual pH of the soil. The buffered methods (NH_4^+ at pH 7.0 or Ba^{2+} at pH 8.2) measure the *potential* or *maximum* cation exchange capacity of a soil. The unbuffered method measures only the **effective cation exchange capacity** (ECEC), which can hold exchangeable cations at the pH of the soil as sampled. As the different methods

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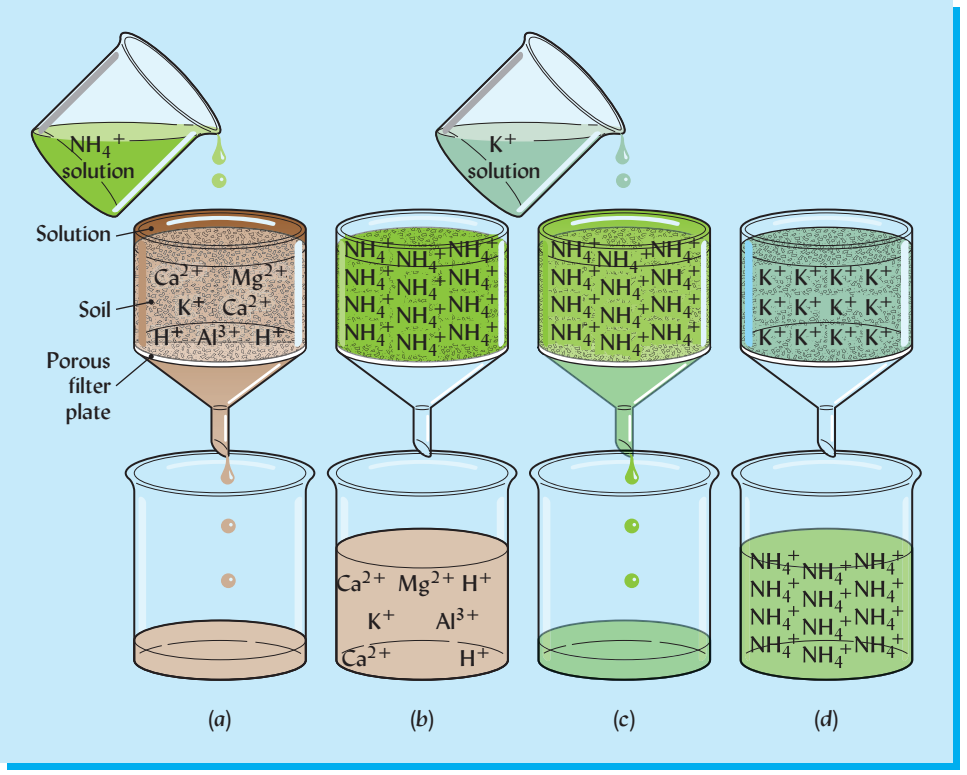

Figure 8.27 *Illustration of a method for determining the cation exchange capacity of soils.* (a) *A given mass of soil containing a variety of exchangeable cations is leached with an ammonium (NH_4^+) salt solution.* (b) *The NH_4^+ ions replace the other adsorbed cations, which are leached into the container below.* (c) *After the excess NH_4^+ salt solution is removed with an organic solvent, such as alcohol, a K^+ salt solution is used to replace and leach the adsorbed NH_4^+ ions.* (d) *The amount of NH_4^+ released and washed into the lower container can be determined, thereby measuring the chemical equivalent of the cation exchange capacity (i.e., the negative charge on the soil colloids).* (Diagram courtesy of Ray R. Weil)

BOX 8.6

CALCULATING SOIL CEC FROM LAB DATA

Most procedures for measuring soil CEC use cation exchange reactions similar to those illustrated in Figure 8.27. The various cations initially adsorbed by the soil colloids are replaced by exposing the soil sample to a salt solution containing an overwhelming number of cations of a single element. The element chosen is usually one not found in large quantities on the soil exchange complex (e.g., NH_4^+, Ba^{2+}, or Sr^{2+}). Examine Figure 8.24 and assume that 100 g (0.1 kg) of dry soil was placed in the funnel and that 400 mL (0.4 L) of solution was added at each step. There are two methods by which one can then estimate the CEC of the soil.

METHOD 1: MEASURE ALL THE CATIONS ORIGINALLY HELD ON THE EXCHANGE COMPLEX

After leaching the soil with 0.4 L of NH_4^+ solution, all the exchangeable cations shown in the soil sample in Figure 8.27a were displaced off the colloids and washed into the beaker (Figure 8.27*b*) along with the excess NH_4^+ ions. The solution in this beaker (*b*) was analyzed for Ca, Mg, K, Al, and H with the following results: 200 mg/L Ca^{2+}, 60 mg/L Mg^{2+}, 97.5 mg/L K^+, 5 mg/L H^+, and 67.5 mg/L Al^{3+}. Because only 0.4 L of solution was collected from the soil sample and the soil sample weighed only 0.1 kg, these results can be multiplied by 0.4 and 10 to give the amounts of each ion collected in mg/kg soil. As an example we can show the calculation for Ca^{2+} as:

$$\frac{200 \text{ mg } Ca^{2+}}{\text{L}} \times \frac{0.4 \text{ L}}{\text{sample}} \times \frac{10 \text{ samples}}{\text{kg soil}} = \frac{800 \text{ mg } Ca^{2+}}{\text{kg soil}}$$

Similar calculations show that the concentration of exchangeable cations in the soil were: 800 mg Ca^{2+}/kg, 240 mg Mg^{2+}/kg, 390 mg K^+/kg, 20 mg H^+/kg, and 270 mg Al^{3+}/kg. The CEC is normally expressed as the cmol of charge per kg of soil ($cmol_c$/kg). Since the atomic weight of an element is defined as the grams per mole of that element, we now turn to the periodic table in Appendix B for the atomic weights (g/mol) needed to convert our mg/kg concentrations into mol/kg for each cation species measured. We divide the mg/kg soil (from above) by 1000 to give g/kg and then divide by the atomic weight to give mol/kg soil. We then multiply the mol by 100 to give the $cmol_c$/kg soil (see Box 8.5).

For example, for Ca^{2+} the atomic weight is approximately 40 g/mol, so we calculate the cmol of exchangeable Ca^{2+} in 1 kg of our soil as follows:

$$\frac{800 \text{ mg } Ca^{2+}}{\text{kg soil}} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol } Ca^{2+}}{40 \text{ g}} \times \frac{100 \text{ cmol}}{\text{mol}} = \frac{2 \text{ cmol } Ca^{2+}}{\text{kg soil}}$$

(continued)

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BOX 8.6

CALCULATING SOIL CEC FROM LAB DATA *(CONTINUED)*

Repeating this calculation for each element provides the following results: 2 cmol Ca^{2+}/kg, 1 cmol Mg^{2+}/kg, 1 cmol K^+/kg, 2 cmol H^+/kg, and 1 cmol Al^{3+}/kg. We now must multiply the cmol/kg for each element by the valence of the ion to convert to the cmol of *charge* ($cmol_c$/kg) from that element. Using Ca^{2+} again as an example:

$$\frac{2 \text{ cmol } Ca^{2+}}{\text{kg soil}} \times \frac{2 \text{ cmol}_c \text{ from } Ca^{2+}}{\text{cmol } Ca^{2+}} = \frac{4 \text{ cmol}_c \text{ from } Ca^{2+}}{\text{kg soil}}$$

Repeating this calculation provides the following results: 4 $cmol_c$ Ca^{2+}/kg, 2 $cmol_c$ Mg^{2+}/kg, 1 $cmol_c$ K^+/kg, 2 $cmol_c$ H^+/kg, and 3 $cmol_c$ Al^{3+}/kg. Assuming the five elements measured account for nearly all the exchangeable cations, the sum of their charges (4 + 2 + 1 + 2 + 3 = 12) equals the CEC of our soil: 12 $cmol_c$/kg.

METHOD 2: MEASURE ALL THE NH_4^+ IONS IN THE FINAL LEACHATE

Assume that after washing out and discarding all excess (nonexchangeable) ions, the remaining exchangeable ions were replaced by K^+ ions and washed into beaker *d* (Figure 8.27). Therefore the number of charges from NH_4^+ ions in beaker *d* is equal to the CEC of the soil. Note that by this method, the lab needs to determine only one element. Assume the NH_4^+ concentration in beaker *d* to be 540 mg NH_4^+/L. As in method 1 (above), because only 0.4 L of solution was collected from the soil sample and the soil sample weighed only 0.1 kg, these results can be calculated as follows to give the amount of NH_4^+ ions collected in mg/kg soil:

$$\frac{540 \text{ mg } NH_4^+}{\text{L}} \times \frac{0.4 \text{ L}}{\text{sample}} \times \frac{10 \text{ samples}}{\text{kg soil}} = \frac{2160 \text{ mg } NH_4^+}{\text{kg soil}}$$

The periodic table in Appendix B provides the atomic weights needed to convert our mg NH_4^+/L concentration into mol NH_4^+/kg. We divide the mg/kg (from above) by 1000 to give g/kg. Using atomic weights from the periodic table (Appendix B) we calculate that 1 mol of NH_4^+ = 18 g [14g/mol N + 4(1 g/mol H) = 18 g/mol NH_4^+]. We then divide the g/kg by the 18 g/mol to give the moles of NH_4^+. We then multiply the moles NH_4^+ by 100 to give the $cmol_c$/ kg (see Box 8.5). We can therefore calculate the cmol of exchangeable NH_4^+ in 1 kg of our soil as follows:

$$\frac{2160 \text{ mg } NH_4^+}{\text{kg soil}} \times \frac{1 \text{ mol } NH_4^+}{10 \text{ g}} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{100 \text{ cmol}}{\text{mol}} = \frac{12 \text{ cmol } NH_4^+}{\text{kg soil}}$$

Since each ion carries only 1 charge, the cmol of *charge* from NH_4^+ ($cmol_c$/kg) is the same as the cmol NH_4^+/kg:

$$\frac{12 \text{ cmol } NH_4^+}{\text{kg soil}} \times \frac{1 \text{ cmol}_c \text{ from } NH_4^+}{\text{cmol } NH_4^+} = \frac{12 \text{ cmol}_c \text{ from } NH_4^+}{\text{kg soil}}$$

Therefore the CEC of our soil = 12 $cmol_c$/kg. [If you happened to count the ions in Figure 8.24, you may have noticed that the concentrations chosen here are those that would apply if each ion shown actually represented 1 cmol of ions.]

may yield significantly different values of CEC, it is important that the method used be known when comparing soils based on their CEC. This is especially significant if the soil pH is much below the buffer pH used.

Cation Exchange Capacities of Soils

The CEC of a given soil sample is determined by the relative amounts of different colloids in that soil and by the CEC of each of these colloids. Figure 8.28 illustrates the common range of CEC for different soils and other organic and inorganic exchange materials. Note that sandy soils, which are generally low in all colloidal material, have low CECs compared to those exhibited by silt loams and clay loams. Also note the very high CECs associated with humus compared to those exhibited by the inorganic clays, especially kaolinite and Fe, Al oxides. The CEC coming from humus generally plays a very prominent role, and sometimes a dominant one, in cation exchange reactions in A horizons. For example, in a clayey Ultisol (pH = 5.5) containing 2.5% humus and 30% kaolinite, about 75% of the CEC is associated with humus. Figure 8.29 illustrates the contribution of organic matter to the CEC of various forested soils and how that contribution increases at higher soil pH levels.

Using the CEC ranges from Figure 8.28 or Table 8.4 it is possible to estimate the CEC of a soil if the quantities of the different soil colloids in the soil are known (see Box 8.7).

Data in Table 8.7 show the range of CEC values characteristic for soils in different soil orders. Note the very high CEC for the Histosols, reflecting the high CEC of the organic

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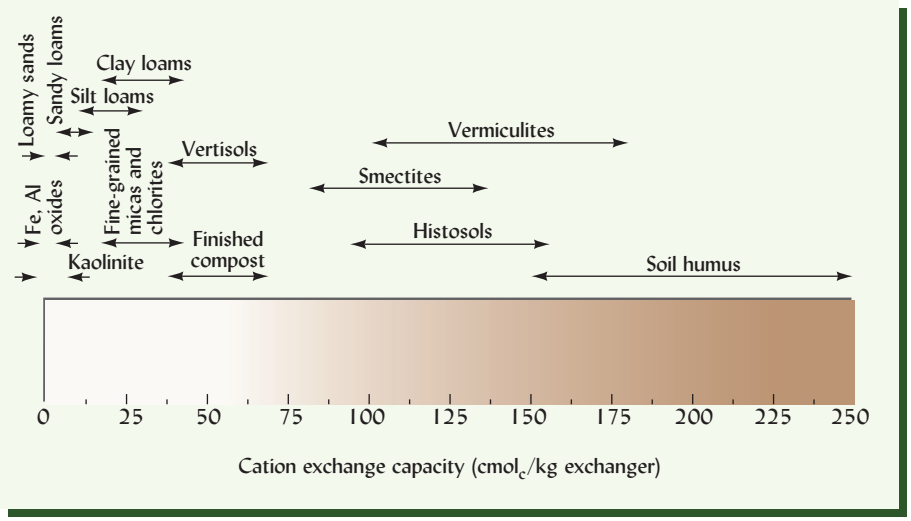

Figure 8.28 *Ranges in the cation exchange capacities (at pH 7) that are typical of a variety of soils and soil materials. The high CEC of humus shows why this colloid plays such a prominent role in most soils and especially those high in kaolinite and Fe, Al oxides, and clays that have low CECs.* (Diagram courtesy of Ray R. Weil)

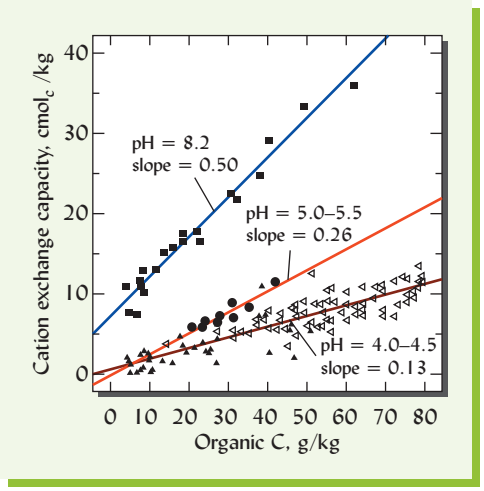

Figure 8.29 *Soil organic carbon (SOC) contributes markedly to the cation exchange capacity (CEC) of soils and more so at higher pH levels. In this graph, the sloping lines indicate the relationship between increasing SOC and CEC. The greater slopes for the higher pH soils indicate that the CEC of humus increases with increased pH. At pH 4.0–4.5, every 1 g increase in organic C contributed to the CEC an additional 0.13 cmol$_c$/kg soil. At the pH 5.0–5.5 level, this contribution was twice as great (0.26 cmol$_c$) and at pH 8.2 the contribution was about four times as great (0.50 cmol$_c$). At each pH level the data represent soils with similar clay contents, but with SOC contents that varied because of differences in soil depth or land use.* [Data sources: squares and filled triangles, Krishnaswamy and Richter (2002); circles, Bayer et al. (2001); open triangles, Sullivan et al. (2006)]

BOX 8.7

ESTIMATING CEC AND CLAY MINERALOGY

Data on clay mineralogy and cation exchange capacity are rather time-consuming to obtain and not always available. Fortunately, one can often estimate one of these types of data from the other, assuming that data on soil pH, clay content, and organic matter level are available.

1. Example of Estimating CEC from Data on Mineralogy

Assume you know that a cultivated Mollisol in Iowa contains 20% clay and 4% organic matter (OM) and its pH = 7.0. The dominant clays in Mollisols are likely 2:1 types such as vermiculite and smectite (see Table 8.3). We estimate the average CEC of the clays of these types to be about 100 cmol$_c$/kg clay (Tables 8.1 and 8.4). At pH 7.0 the CEC of OM is about 200 cmol$_c$/kg (Table 8.4). Since 1 kg of this soil has 0.20 kg (20%) of clay and 0.04 kg (4%) of OM, we can calculate the CEC associated with each of these sources.

From the clays in this Mollisol: $0.2 \text{ kg} \times 100 \text{ cmol}_c/\text{kg} = 20 \text{ cmol}_c$

From the OM in this Mollisol: $0.04 \text{ kg} \times 200 \text{ cmol}_c/\text{kg} = 8 \text{ cmol}_c$

The total CEC of this Mollisol: $20 + 8 = 28 \text{ cmol}_c/\text{kg soil}$

2. Example of Estimating the Clay Mineralogy from Information on CEC

Assume you know that a soil contains 60% clay and 4% organic matter and the pH = 4.2. You also know the CEC is 5.8 cmol$_c$/kg. You want to estimate the types of clays

(continued)

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BOX 8.7

ESTIMATING CEC AND CLAY MINERALOGY *(CONTINUED)*

present. At pH 4.2 the CEC of the organic matter would be comparatively low, about 100 $cmol_c$/kg (Figure 8.21). Therefore we estimate:

$$\text{CEC from OM in 1 kg soil} = 0.04 \text{ kg OM} \times 100 \text{ cmol}_c\text{/kg OM} = 4.0 \text{ cmol}_c$$

The remaining portion of the CEC contributed by the clay can be estimated as:

$$\text{CEC from the clay in 1 kg soil} = 5.8 \text{ cmol}_c - 4.0 \text{ cmol}_c = 1.8 \text{ cmol}_c$$

Since this 1.8 $cmol_c$/kg soil is provided by 0.60 kg of clay (60% of 1 kg soil), we can estimate:

$$\text{CEC of the pure clay} = 1.8 \text{ cmol}_c\text{/kg soil} \times 1 \text{ kg soil}/0.60 \text{ kg clay} = 3 \text{ cmol}_c\text{/kg clay}$$

From Tables 8.1 and 8.4 we see that the Fe and Al oxides at pH 7 have a CEC of about 4 $cmol_c$/kg clay. We know (from Section 8.6) their CEC would be lower at pH 4. Likewise, kaolinite has a CEC of about 8 $cmol_c$/kg clay at pH 7 and perhaps only about 4 $cmol_c$/kg clay at pH 4. The CEC values for the other types of clay listed in Table 8.4 are far higher. *Therefore, it is reasonable to conclude that the clays in this soil consist mainly of Fe and Al oxides and kaolinite.*

Table 8.7
COMMON RANGES OF POTENTIAL CATION EXCHANGE CAPACITIES IN THE SURFACE LAYERS (A AND B HORIZONS) OF SOILS IN DIFFERENT SOIL ORDERS

Organic colloids give Histosols a very high CEC. Compare to data in Tables 8.3 and 8.4 to see the relationship between the average CEC and the main types of colloids in the other soil orders. The wide range of CEC within each soil order is largely a result of variations in the amount of clay and organic matter in the individual soils.

Soil order	Common range of CEC,[a] $cmol_c$/kg	Soil order	Common range of CEC, $cmol_c$/kg
Histosols	110–170	Inceptisols & Entisols	5–37
Vertisols	33–67	Aridisols	7–29
Andisols	13–49	Alfisols	4–26
Spodosols	2–57	Ultisols	3–15
Mollisols	12–36	Oxisols	2–13

[a]The CEC was measured on a total of approximately 1000 soils using methods buffered at pH 7.0 or 8.2 and therefore may overestimate CEC for more acid soils and underestimate CEC for more alkaline soils. The range given is one standard deviation above and below the mean for the samples analyzed and thus can be expected to include roughly 70% of the soils in the indicated soil order. Gelisols were not listed, but were included in either the Histosols or Inceptisols. From Essington (2004).

colloids. The Vertisols, which are very high in swelling-type clays (mostly smectite), have the highest average CEC of the mineral soils. Andisols and Spodosols are commonly high in organic matter and, in the case of Andisols, allophane and smectitic-type clays. Ultisols and Oxisols, whose clays are dominantly kaolinite and hydrous oxides of iron and aluminum, have relatively low CEC values. Despite large variations in soil organic matter and texture, these data appear to reflect the quantities and kinds of colloids found in the soils.

pH and Cation Exchange Capacity

In previous sections it was pointed out that the cation exchange capacity of most soils increases with pH. At very low pH values, the cation exchange capacity is also generally low (Figure 8.30). Under these conditions, only the permanent charges of the 2:1-type clays (see

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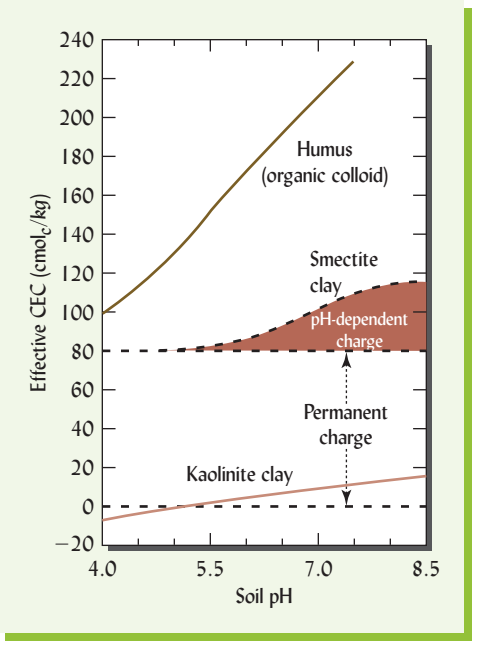

Figure 8.30 *Influence of pH on representative cation exchange capacities of two clay minerals and humus. Below pH 6.0 the charge for smectite has a fairly constant charge that is due mainly to isomorphic substitution and is considered permanent. Above pH 6.0 the charge on smectite increases somewhat with pH (shaded area) because of the ionization of hydrogen from the exposed hydroxyl groups at crystal edges. In contrast, the charges on kaolinite and humus are all variable, increasing with increasing pH. Humus carries a far greater number of charges than kaolinite. At low pH kaolinite carries a net negative CEC because its positive charges outnumber the negative ones.* (Diagram courtesy of N. Brady and Ray R. Weil)

Section 8.8) and a small portion of the pH-dependent charges of organic colloids, allophane, and some 1:1-type clays hold exchangeable ions. As the pH is raised, the negative charges on some 1:1-type silicate clays, allophane, humus, and even Fe, Al oxides increases, thereby increasing the cation exchange capacity. As noted earlier, to obtain a measure of this maximum retentive capacity, the CEC is commonly determined at a pH of 7.0 or 8.2. At neutral or slightly alkaline pH, the CEC reflects most of those pH-dependent charges as well as the permanent ones.

8.10 EXCHANGEABLE CATIONS IN FIELD SOILS

The specific exchangeable cations associated with soil colloids differ from one climatic region to another; Ca^{2+}, Al^{3+}, complex aluminum hydroxy ions, and H^+ are most prominent in humid regions, while Ca^{2+}, Mg^{2+}, and Na^+ dominate soil in low-rainfall areas (Table 8.8).

In a given soil, the proportion of the cation exchange capacity satisfied by a particular cation is termed the ***saturation percentage*** for that cation. Thus, if 50% of the CEC is satisfied by Ca^{2+} ions, the exchange complex is said to have a ***calcium saturation percentage*** of 50. The cations that dominate the exchange complex have a marked influence on soil properties.

This terminology is especially useful in identifying the relative proportions of sources of acidity and alkalinity in the soil solution. Thus, the percentage saturation with Al^{3+} and H^+ ions gives an indication of the acid conditions, while increases in the percentage **nonacid cation saturation** (sometimes referred to as the ***base saturation percentage***[3]) indicate the tendency toward neutrality and alkalinity. These relationships will be discussed further in Section 9.1.

Cation Saturation and Nutrient Availability

Exchangeable cations generally are available for uptake by both higher plants and microorganisms. By cation exchange, hydrogen ions from root hairs and microorganisms replace nutrient cations from the exchange complex. The nutrient cations are forced into the soil solution, where they can be assimilated by the adsorptive surfaces of roots and soil organisms, or they may be removed by drainage water. Cation exchange reactions affecting the mobility of

[3]Nonacid cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ are not true bases. When adsorbed by soil colloids in the place of Al^{3+} and H^+ ions, however, they reduce acidity and increase the soil pH. For that reason, they are traditionally referred to as *bases* and the portion of the CEC that they satisfy is often termed *base saturation percentage*.

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Table 8.8
CATION EXCHANGE PROPERTIES TYPICAL FOR UNAMENDED CLAY LOAM SURFACE SOILS IN DIFFERENT CLIMATIC REGIONS
Note that soils with coarser textures would have less clay and organic matter and therefore lower amounts of exchangeable cations and lower CEC values.

Property	Warm, humid region (Ultisols)[a]	Cool, humid region (Alfisols)	Semiarid region (Ustolls)	Arid region (Natrargids)[b]
Exchangeable H^+ and Al^{3+}, $cmol_c$/kg (% of CEC)	7.5 (75%)	5 (28%)	0 (0%)	0 (0%)
Exchangeable Ca^{2+}, $cmol_c$/kg (% of CEC)	2.0 (20%)	9 (50%)	17 (65%)	13 (50%)
Exchangeable Mg^{2+}, $cmol_c$/kg (% of CEC)	0.4 (4%)	3 (17%)	6 (23%)	5 (19%)
Exchangeable K^+, $cmol_c$/kg (% of CEC)	0.1 (1%)	1 (5%)	2 (8%)	3 (12%)
Exchangeable Na^+, $cmol_c$/kg (% of CEC)	Tr	0.02 (0.1%)	1 (4%)	5 (19%)
CEC,[c] $cmol_c$/kg	10	18	26	26
Probable pH	4.5–5.0	5.0–5.5	7.0–8.0	8–10
Nonacid cations (% of CEC)[d]	25%	68%	100%	100%

[a]See Chapter 3 for explanation of soil group names.
[b]Natrargids are Aridisols with natric horizons. They are sodic soils, high in exchangeable sodium, as explained in Section 10.5.
[c]The sum of all the exchangeable cations measured at the pH of the soil. This is termed the effective CEC or ECEC (see Section 8.9).
[d]Traditionally referred to as "base" saturation.

organic and inorganic pollutants in soils will be discussed in Section 8.12. Here we focus on the plant nutrition aspects.

The percentage saturation of essential nutrient cations such as calcium and potassium greatly influences the uptake of these elements by growing plants. For example, if the percentage calcium saturation of a soil is high, the displacement of this cation is comparatively easy and rapid. Thus, 6 cmol/kg of exchangeable calcium in a soil whose exchange capacity is 8 cmol/kg (75% calcium saturation) probably would mean ready availability, but 6 cmol/kg when the total exchange capacity of a soil is 30 cmol/kg (20% calcium saturation) would produce lower availability. This is one reason that, calcium-loving plants such as alfalfa grow best when the calcium saturation of at least part of the soil approaches 75–85%.

Influence of Complementary Cations

A second factor influencing plant uptake of a given cation is the effect of the complementary ions held on the colloids. As was discussed in Section 8.8, the strength of adsorption of common cations on most colloids is in the order: $Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ = NH_4^+ > Na^+$.

For example, if the complementary ions surrounding a K^+ ion are held tightly (i.e., they oscillate very close to the colloid surface), then a H^+ ion from a root is less likely to "find" a complementary ion than "bump into" and replace a K^+ ion (see Figure 8.31). If, on the other hand, the complementary ions are loosely held (oscillating quite far from the colloid surface), then the H^+ is more likely to "bump into" and replace one of the complementary ions and less likely to "find" the K^+. Consequently, K^+ is more likely to be replaced off the colloid if the complementary ions are mainly tightly held Al^{3+} or H^+ (as in acid soils) than if they are mainly Mg^{2+} and Na^+ (as in neutral to alkaline soils). This is why, at a given level of K^+ saturation, K^+ is more readily available for both plant uptake and for leaching in acid soils than in neutral to alkaline soils (see also Section 14.13).

There are also some nutrient antagonisms that in certain soils cause inhibition of uptake of some cations by plants. For instance, potassium uptake by plants is limited by high levels

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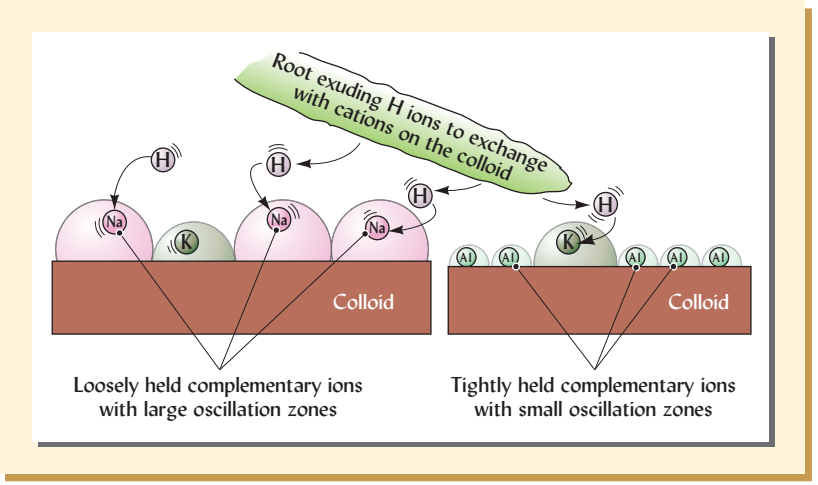

Figure 8.31 *Effect of complementary ions on the availability of a particular exchangeable nutrient cation. The half spheres represent the zones in which the ion oscillates, the more loosely held ions moving within larger zones of oscillation. For simplicity, the water molecules that hydrate each ion are not shown.* (Left) *H^+ ions from the root are more likely to encounter and exchange with loosely held Na^+ ions rather than the more tightly held K^+ ion.* (Right) *The likelihood that H^+ ions from the root will encounter and exchange with a K^+ ion is increased by the inaccessibility of the neighboring tightly held Al^{3+} ions. The K^+ ion on the right colloid is comparatively more vulnerable to being replaced and sent into the soil solution and is therefore more available for plant uptake or leaching than the K^+ ion on the left colloid.* (Diagram courtesy of Ray R. Weil)

of calcium in some soils. Likewise, high potassium levels are known to limit the uptake of magnesium even when significant quantities of magnesium are present in the soil. These antagonisms, however, are more related to competition in the plant uptake process than to soil exchange properties.

Effect of Type of Colloid

Differences exist in the tenacity with which several types of colloids hold specific cations and in the ease with which they exchange cations. At a given percentage base saturation, smectites—which have a high charge density per unit of colloid surface—hold calcium much more strongly than does kaolinite (low charge density). As a result, smectite clays must be raised to about 70% base saturation before calcium will exchange easily and rapidly enough to satisfy many plants. In contrast, a kaolinite clay exchanges calcium much more readily, serving as a satisfactory source of this constituent at a much lower percentage base saturation. The need to add limestone to the two soils will be somewhat different, partly because of this factor. We will now turn our attention from the exchange of cations to the exchange of anions.

8.11 ANION EXCHANGE

Anions are held (**sorbed**) by soil colloids in two major ways. First, they are held by anion adsorption mechanisms similar to those responsible for cation exchange. Second, they may actually react with surface oxides or hydroxides, forming more definitive **inner-sphere complexes**. We shall consider anion adsorption first.

The basic principles of **anion exchange** are similar to those of cation exchange, except that the charges on the colloids are positive and the exchange is among negatively charged anions. The positive charges associated with the surfaces of kaolinite, iron and aluminum oxides, and allophane attract anions such as SO_4^{-2} and NO_3^-. A simple example of an anion exchange reaction is as follows:

$$\underset{\text{(positively charged soil solid)}}{\boxed{\text{Colloid}}}\ \underset{\text{(soil solution)}}{NO_3^- + Cl^-} \rightleftharpoons \underset{\text{(positively charged soil solid)}}{\boxed{\text{Colloid}}}\ \underset{\text{(soil solution)}}{Cl^- + NO_3^-} \tag{8.11}$$

Just as in cation exchange, ***equivalent*** quantities of NO_3^- and Cl^- are exchanged; the reaction can be reversed, and nutrient anions so released can be absorbed by plants.

In contrast to cation exchange capacities, anion exchange capacities (AEC) of soils generally *decrease* with increasing pH. Figure 8.32 illustrates this fact for an Ultisol in southern United States. In some very acid tropical soils that are high in kaolinite and iron and aluminum oxides, the anion exchange capacity may actually exceed the cation exchange capacity.

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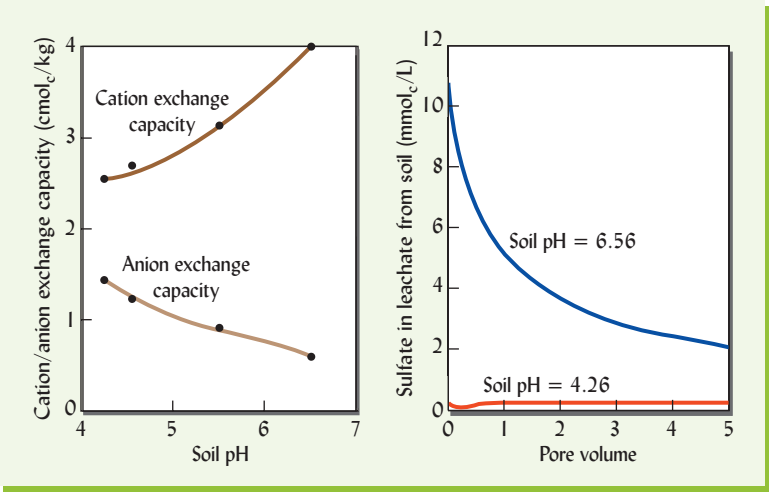

Figure 8.32 (Left) *Effect of increasing the pH of subsoil material from an Ultisol on the cation and anion exchange capacities (CEC and AEC) and sulfate sorption. The anion exchange capacity declined as the soil pH increased.* (Right) *When a column of the higher AEC material (pH = 4.26) was leached with $Ca(NO_3)_2$ little sulfate was removed from the soil. In contrast, similar leaching of a column of the soil with the lowest AEC (at pH 6.56), resulted in anion exchange of NO_3^- ions for SO_4^{-2} ions and significant leaching of sulfate from the soil. The importance of anion adsorption in retarding movement of negatively charged substances is illustrated.* [Data from Bellini et al. (1996)]

Anion exchange is very important in making anions available for plant growth while at the same time retarding the leaching of such anions from the soil. For example, anion exchange restricts the loss of sulfates from subsoils in the southern United States (see Figure 8.32 and Section 13.21). Even the leaching of nitrate may be retarded by anion exchange in the subsoil of certain highly weathered soils of the humid tropics. Similarly, the downward movement into groundwater of some charged organic pollutants found in organic wastes can be retarded by such anion and/or cation exchange reactions.

Inner-Sphere Complexes

Some anions, such as phosphates, arsenates, molybdates, and sulfates, can react with particle surfaces, forming **inner-sphere complexes** (see Figure 8.20). For example, the $H_2PO_4^-$ ion may react with the protonated hydroxyl group rather than remain as an easily exchanged anion

$$\underset{\text{(soil solid)}}{>\!\!\text{Al}\!-\!\text{OH}_2^+} + \underset{\text{(soil solution)}}{\text{H}_2\text{PO}_4^-} \longrightarrow \underset{\text{(soil solid)}}{>\!\!\text{Al}\!-\!\text{H}_2\text{PO}_4} + \underset{\text{(soil solution)}}{\text{H}_2\text{O}} \tag{8.12}$$

This reaction actually reduces the net positive charge on the soil colloid. Also, the $H_2PO_4^-$ is held very tightly by the soil solids and is not readily available for plant uptake.

Anion adsorption and exchange reactions regulate the mobility and availability of many important ions. Together with cation exchange they largely determine the ability of soils to hold nutrients in forms that are accessible to plants and to retard movement of pollutants in the environment.

Weathering and CEC/AEC Levels

Clays developed under mild weathering conditions (e.g., smectites and vermiculites) have much higher CEC levels than those developed under more extreme weathering pressures (Figure 8.33). The AEC levels, in turn, tend to be much higher in clays developed under strong weathering conditions (e.g., kaolinite) than in those found under milder weathering. In addition to the climate, the nature of the parent material and the time allowed for the weathering to occur also influence the clay types present and the CEC/AEC relations. The generalized relationships in Figure 8.33 are helpful in obtaining a first approximation of CEC and AEC levels in soils of different soil orders.

These relationships are validated by many studies using real soils to adsorb specific ions, such as the one featured in Figure 8.34 showing adsorption of toxic cadmium cations (Cd^{2+}) on four soils of different clay mineralogy in China. The two soils (Alfisols and Inceptisols) highest in 2:1 clays exhibited much higher CEC and greater capacities to adsorb cations ions from the soil solution. For all four soils, the amount of Cd^{2+} adsorbed increased as each soil was equilibrated with increasingly concentrated solutions of Cd^{2+}, with the amount adsorbed

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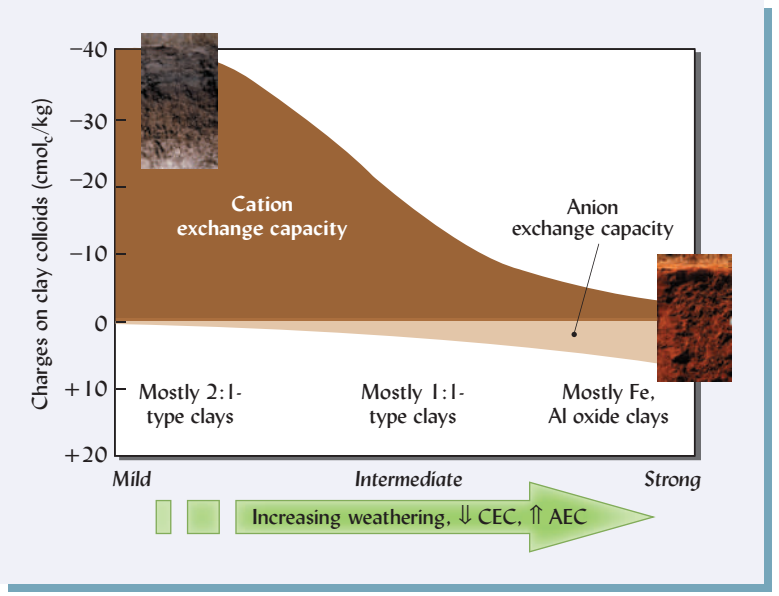

Figure 8.33 *The effect of weathering intensity on the charges on clay minerals and, in turn, on their cation and anion exchange capacities (CECs and AECs). Note the high CEC and very low AEC associated with mild weathering, which has encouraged the formation of 2:1-type clays such as fine-grained micas, vermiculites, and smectites. More intense weathering destroys the 2:1-type clays and leads to the formation of first kaolinite and then oxides of Fe and Al.* (Courtesy of Ray R. Weil)

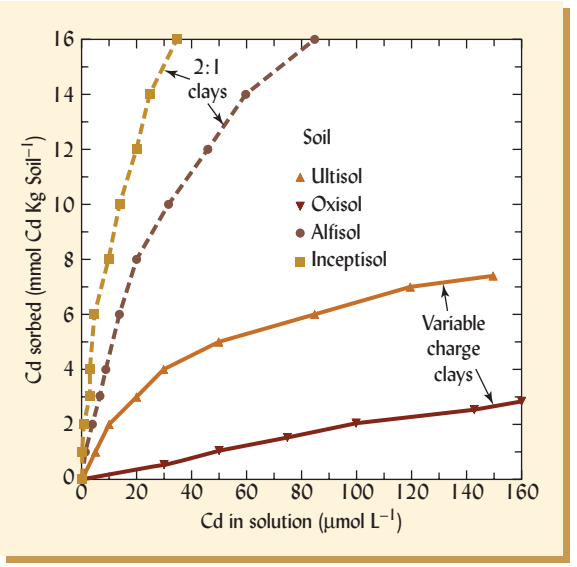

Figure 8.34 *Sorption of cadmium (Cd, a toxic heavy metal) on four Chinese soils varying in their degree of weathering, and therefore type of clay mineralogy. The more Cd^{2+} is sorbed to (held by) the soil colloids, the less it is likely to leached to groundwater or taken up by vegetation. The amount of Cd^{2+} sorbed onto the soils increased as each soil was equilibrated with increasingly concentrated solutions of $Cd(N0_3)_2$, with the amount leveling off as the maximum sorptive capacity of each soil was approached. Such curves are termed sorption isotherms and illustrate adsorption by both outer- and inner-sphere complexation.* [Redrawn from Hu et al. (2007)]

leveling off as the maximum sorptive capacity of each soil was approached. Such curves are termed **sorption isotherms**.

8.12 SORPTION OF PESTICIDES AND GROUNDWATER CONTAMINATION

Soil colloids can sorb charged organic molecules as well as the inorganic cations emphasized in this chapter so far. Thus the retentive properties of soil colloids help control the biological activity of such organic compounds as pesticides and retard their movement into groundwater (Figure 8.35). The retention of these chemicals by soil colloids can allow time for soil microbes to break the chemicals down into less toxic byproducts. Retention by soil colloids may also inactivate organic compounds, especially those that have positively charged sites that can interact with the soil CEC (Figure 8.36).

By accepting or releasing protons (H^+ ions), groups such as —OH, —NH_2, and —COOH in the chemical structure of many organic compounds provide positive or negative

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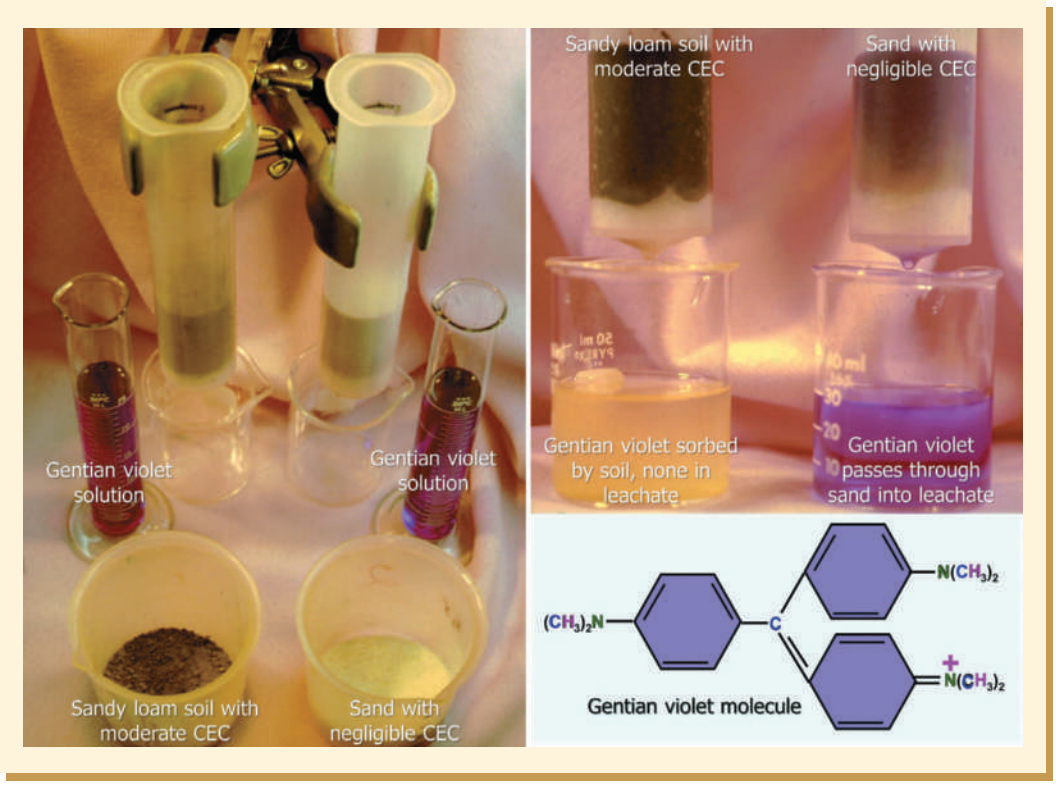

Figure 8.35 *Retention of a soluble positively charged organic compound (the purple dye, Gentian violet) by the process of cation exchange in soil.* (Left) *The experimental setup is shown before adding the gentian violet solution to the soil in the columns. The left-hand beaker and column contain a sandy loam soil with a moderate CEC (10 cmol$_c$/kg) while the right-hand beaker and column contain a sand with negligible CEC (<1 cmol$_c$/kg).* (Right) *After the gentian violet solutions were poured into the columns and leached through the soils, the water draining from the soil is clear with no purple color, indicating that the CEC of the soil has removed all the Gentian violet from the solution. In contrast, the water draining from the sand column is still purple; only a small portion of the compound was retained by the very small CEC of the sand. It requires little imagination to see how soils can thereby protect groundwater from pesticides and other organic contaminants.* (Photos courtesy of Ray R. Weil)

Figure 8.36 *A wheat field in southern Africa illustrates the importance of soil CEC for the sorption of organic compounds. These Alfisols have sandy A horizons with low CEC (~4 cmol$_c$/kg) but clayey subsoil (argillic) horizons with higher CEC (~12 cmol$_c$/kg). The whole field was treated with weed-killing organic chemicals (herbicides). So why did the herbicides fail to do their job in the three "islands" of tall green weedy vegetation that stand in contrast to the weed-free golden-colored wheat nearing harvest maturity? It turns out that in these three area bulldozers had leveled large mounds made from clayey subsoil material brought up by termites. In these areas, the cationic (positively charged) herbicide molecules were sorbed tightly to the clays so they were no longer available to be taken up by the roots of the weeds. In fact the rate of application for some pesticides must be adjusted for the CEC of the soil if an effective amount of the chemical is to remain in solution where it can interact with its intended targets.* (Photo by Ray R. Weil)

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charges that participate in anion or cation exchange reactions. Other organic compounds participate in inner-sphere complexation and adsorption reactions just as do the inorganic ions we have discussed. However, it is common for organic compounds to be **absorbed** within the soil organic colloids by a process termed **partitioning**. The soil organic colloids tend to act as a solvent for the applied chemicals, thereby partitioning their concentrations between those molecules held on/in the soil colloids and those left in the soil solution.

Since we seldom know for certain the exact involvement of the adsorption, complexation, or partitioning processes, we use the general term **sorption** to describe the retention by soils of these organic compounds. Nonionic organic compounds are **hydrophobic**, being repelled by water. As a result, moist clays contribute little to their partitioning since their adsorbed water molecules prevent the movement of the nonionic organic chemicals into or around the clay particles. The hydrated metal cations (e.g., Ca^{2+}) that are adsorbed on the surface of smectites can be replaced with large organic cations, giving rise to what are termed **organoclays**. Such clay surfaces are more friendly toward applied organic compounds, making it possible for the clay to participate in partitioning. Environmental scientists use this phenomenon by making smectite organoclays that can remove organic contaminants from wastewaters and from contaminated groundwaters (see Section 18.5).

Distribution Coefficients

The tendency of a pesticide or other organic compound to leach into the groundwater is determined by the solubility of the compound and by the ratio of the amount of chemical sorbed by the soil to that remaining in solution. This ratio is known as the **soil distribution coefficient** K_d

$$K_d = \frac{\text{mg chemical sorbed/kg soil}}{\text{mg chemical/L solution}} \tag{8.13}$$

The K_d therefore is typically expressed in units of L/kg. Researchers have found that the K_d for a given compound may vary widely depending on the nature of the soil in which the compound is distributed. The variation is related mainly to the amount of organic matter (organic carbon) in the soils. Therefore, most scientists prefer to use a similar ratio that focuses on sorption by organic matter. This ratio is termed the organic carbon distribution coefficient K_{oc}:

$$K_{oc} = \frac{\text{mg chemical sorbed/kg organic carbon}}{\text{mg chemical/L solution}} = \frac{K_d}{\text{g org. C/g soil}} \tag{8.14}$$

The K_{oc} can be calculated by dividing the K_d by the fraction of organic C (g/g) in the soil. This relationship can be seen in Table 8.9, which shows both K_d and K_{oc} for several commonly

Table 8.9
PARTITIONING COEFFICIENTS FOR SOIL (K_D) AND FOR ORGANIC CARBON (K_{OC}) FOR SEVERAL WIDELY USED HERBICIDES

Three of the listed compounds are metabolites that form when microorganisms decompose Atrazine. Higher K_d or K_{oc} values indicate stronger attraction to the soil solids and lower susceptibility to leaching loss. The values were measured for a particular soil (an Ultisol in Virginia, USA). Using the relationship between K_d and K_{oc}, it can be ascertained that this soil contained 0.013 g C/g soil (1.3%).

Herbicide	K_d	K_{oc}
Atrazine	1.82	140
Diethyl atrazine	0.99	80
Diisopropyl atrazine	1.66	128
Hydroxy atrazine	7.92	609
Metolachlor	2.47	190

Data from Seybold and Mersie (1996).

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used herbicides and metabolites. Higher K_d or K_{oc} values indicate the chemical is more tightly sorbed by the soil and therefore less susceptible to leaching and movement to the groundwater. On the other hand, if the management objective is to wash the chemical out of a soil, this will be more easily accomplished for chemicals with lower coefficients. Equations (8.13) and (8.14) emphasize the importance of the sorbing power of the soil colloidal complex, and especially of humus, in the management of organic compounds added to soils.

8.13 BINDING OF BIOMOLECULES TO CLAY AND HUMUS[4]

The enormous surface area and number of charged sites on the clay and humus in soils attract and bind many types of organic molecules. These molecules include such biologically active substances as DNA (genetic code material), enzymes, antibiotics, hormones, toxins, and even viruses. The initial attraction may be between charged colloidal surfaces and positively or negatively charged functional groups on the biomolecule, similar to the ion exchange reactions just discussed. The data in Figure 8.37 show that adsorption of biomolecules can take place rapidly (in less than a minute) and the amount adsorbed is related to the type of clay mineral. The bond between the biomolecule and the colloid is often quite strong so that the biomolecule cannot be easily removed by washing or by exchange reactions. In most cases, biomolecules bound to clays do not enter the interlayer spaces, but are attached to the outer planar surfaces and edges of the clay crystals.

The nonexchangeable binding of biomolecules to soil colloids in this manner has important environmental implications for two reasons. First, such binding may protect biomolecules from enzymatic attack, meaning that the molecules will persist in the soil much longer than studies of unbound biomolecules might suggest. Apparently, interaction with the charged colloid surface changes the three-dimensional shape of the biomolecule and its electron distribution so that microbial enzymes, which would normally cleave (cut) the biomolecule, are unable to recognize and react with their target sites. Second, it has been shown that many biomolecules retain their biological activity in the bound state. Toxins remain toxic to susceptible organisms, enzymes continue to catalyze reactions, viruses can lyse (break open) cells or transfer genetic information to host cells, and DNA strands retain the ability to transform the genetic code of living cells, even while bound to colloidal surfaces and protected from decay.

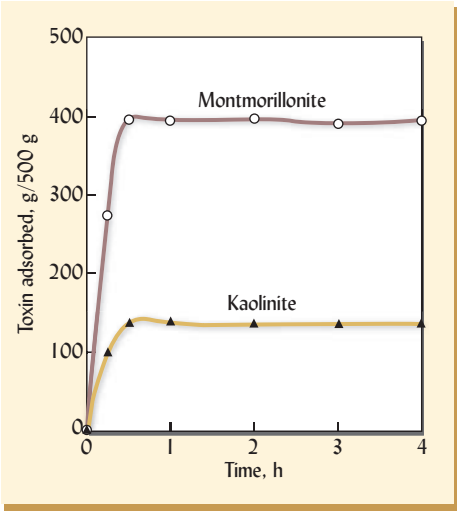

Figure 8.37 *Adsorption of a toxin called* Bt. *This is an insecticidal protein produced by the soil bacteria,* Bacillus thuringiensis, *and used in organic farming to protect crops from insect damage. Highly active clay minerals such as montmorillonite (a member of the smectite group of 2:1 clays) adsorb and bind much larger amounts of these biomolecules than do low-activity clays such as kaolinite (a 1:1 mineral). In both cases, the adsorption reaction was completed in about a minute. Since only 500 μg of either clay mineral was used in the experiment, it appears that the clays adsorbed an amount of the toxin equal to 30–80% of their mass.* [Redrawn from Stotzky (2000)]

[4]For a review of the occurrence and fate of veterinary antibiotics in soil, see Kim et al. (2011).

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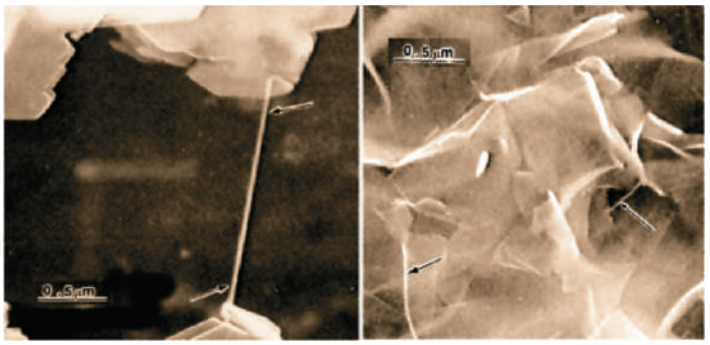

Figure 8.38 *Scanning electron micrographs (SEMs) of DNA from* Bacillus subtilis *bound on kaolinite clay* (left) *and on mont-morillonite clay* (right). *Note the hexagonal crystal shape of the kaolinite and the flake-like shape of the montmorillonite (compare to Figure 8.3a,c). The arrows point to strands of bound DNA. As indicated by the 0.5-μm bars, the clays are magnified about 40,000 times. Research shows that, in soil, DNA bound to clay or humus is protected from decomposition but retains the capability of transferring genetic information to living cells.* (Images courtesy of Dr. Guenther Stotzky, Dept. of Biology, New York University)

Figure 8.38 reveals the nature of one type of organoclay complex involving DNA, a long-chain organic biomolecule. Researchers believe the DNA is adsorbed by hydrogen-bonding to negatively charged sites on clay crystal planar surfaces and by electrostatic attraction of negatively charged DNA to positively charged sites on clay crystal edges. One end of each DNA strand seems to be bound to the colloid, with the other end extended into the soil solution, where it can interact with living cells.

When genetically modified organisms (GMOs) are introduced to the soil environment, the cryptic (hidden) genes just described may represent an undetected potential for transfer of genetic information to organisms for which it was not intended. A similar concern exists regarding plants genetically modified to produce such compounds as human drugs ("pharma crops") or insecticidal toxins. For example, millions of hectares are planted each year with corn and cotton plants genetically engineered to have a bacterial gene that codes for production of the insecticidal toxin Bt (see Figure 8.37). The Bt toxin is released into the soil by root excretion and decomposition of plant residues containing the toxin. We know little about what effect the toxins may have on soil ecology if it accumulates in soils in the colloid-bound, but still active state (see Sections 11.2–11.5).

Antibiotics comprise another class of important organic compounds that sorb to soil colloids. These unique natural chemicals are irreplaceable life-saving compounds. Think of the last time you were given a prescription for an antibiotic drug; had the drug not ended your bacterial infection, the infection may have ended your life! Yet, in most industrial countries, about 80% of antibiotics manufactured are *not* used to cure diseases (in animals or humans) but are used in livestock feed to stimulate faster growth of cattle, swine, and chickens. Not surprisingly, the animal manures produced on most industrial-style farms have been found to be laden with antibiotics that have passed through the animals' digestive systems. When these manures are applied to farmland, the antibiotics become sorbed on the soil colloids and may accumulate with repeated manure applications. Apparently the sorption is very strong. For example, K_d values as high as 2300 L/kg have been reported for the antibiotic tetracycline in some soils (compare this K_d value to those of the herbicides listed in Table 8.9). Many antibiotics appear to interact with soil colloids via the process of cation exchange (Figure 8.39),

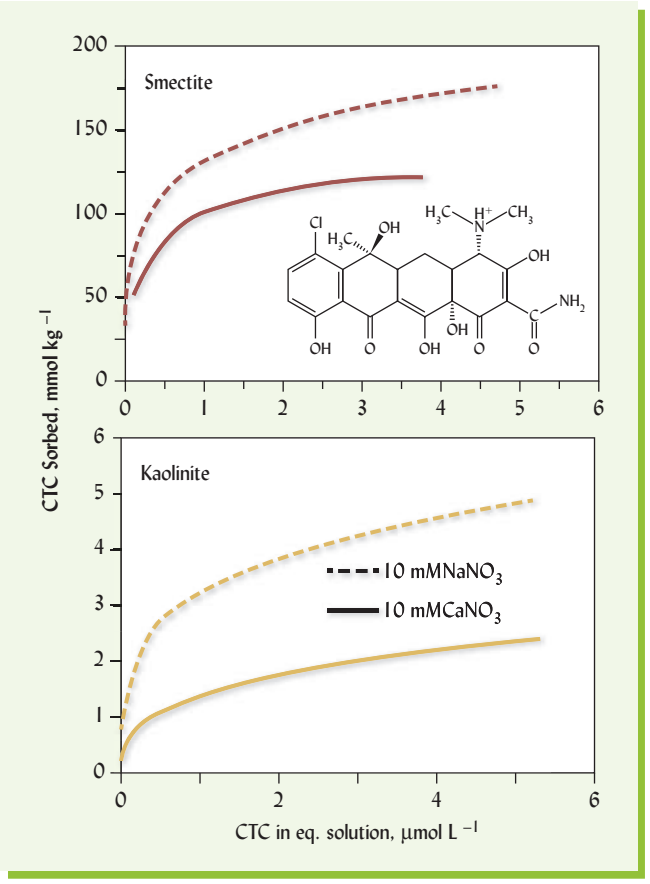

Figure 8.39 *Adsorption isotherms illustrating the retention of chlortetracycline (CTC) by* (a) *montmorillonite (pH 4.3–4.7) and* (b) *kaolinite (pH 5.1–5.6) as a function of ionic background cation. Binding to colloids slowed antibiotic release to microorganisms. Decreasing CTC retention with the inclusion of* $Ca(NO_3)_2$ *as the background electrolyte (relative to* $NaNO_3$*) may also be interpreted to indicate ion exchange because* Ca^{2+} *is more competitive with CTC than* Na^+ *for exchange sites. Greater sorption of CTC with Na background than with Ca background suggests that sorption took place by cation exchange mechanisms since Ca is more tightly held by cation exchange and would be more difficult for CTC to displace.* [Redrawn from Essington et al. (2010)]

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the antibiotic compounds developing positively charged sites, especially in acid soils. Increasingly research shows that even though sorption to soil colloids may reduce their efficacy somewhat, the soil-bound antibiotics still work against bacteria. In addition, there is evidence that at least some antibiotics can be taken up from soil by food crops and so enter the human food supply. These revelations raise concerns that the huge amounts of antibiotics exposed in the environment will select for resistant strains of "super bacteria" (including human pathogens), which would then no longer be controllable by these (once) life-saving drugs. It is clear that soil colloids and soil science have important roles to play with respect to environmental and human health.

8.14 CONCLUSION

The complex structures, enormous surface area (both internal and external), and tremendous numbers of charges associated with soil colloids combine to make these tiniest of soil particles the seats of chemical and physical activity in soils. The physical activity of the colloids, their adsorption of water, swelling, shrinking, and cohesion are discussed in detail in Chapters 4–6. Here we focused on the chemical activity of the colloids, activity that results largely from charged sites on or near colloid surfaces. These charged sites attract oppositely charged ions and molecules from the soil solution. The negative sites attract positive ions (cations) such as Ca^{2+}, Cu^{2+}, K^{+}, or Al^{3+} and the positive sites attract negative ions (anions) such as Cl^{-}, SO_4^{-2}, HPO_4^{2-}, or NO_3^{-}. In most soils the negative charges far outnumber the positive.

Most elements weathered from rocks or added as soil amendments will eventually end up in the oceans, accounting for the increasing saltiness of seawater. Fortunately, colloidal attraction greatly slows that journey and allows soils to accumulate the stocks of nutrients necessary to support forests, grasslands, crops, and, ultimately, civilizations. Colloidal attraction also enables soils to act as effective filters, sinks, and exchangers, protecting groundwater and food chains from excessive exposure to many pollutants.

When ions are attracted to a colloid, they may enter into two general types of relationships with the colloid surface. If the ion bonds directly to atoms of colloidal structure with no water molecules intervening, the relationship is termed an *inner-sphere complex*, and is not easily reversed. In contrast, ions that keep their hydration shell of water molecules around them are generally attracted to colloidal surfaces with excess opposite charge, called *outer-sphere complexation*. The adsorbed ion and its shell of water molecules oscillate or move about within a zone of attraction in a less specific and easily reversed interaction. Ions in such a state of dynamic adsorption are termed *exchangeable ions* because they break away from the colloid whenever another ion from the solution moves in closer and takes over, neutralizing the colloid's charges.

The replacement of one ion for another in the outer-sphere complex is termed *ion exchange.* Cation and anion exchange reactions are reversible and balanced charge-for-charge (rather than ion-for-ion). The extent of the reaction is influenced by mass action, the relative charge and size of the hydrated ions, the nature of the colloid, and the nature of the other (complementary) ions already adsorbed on the colloid.

The colloids in soils are both organic (humus) and mineral (clays) in nature. Organic matter contributes most of the charges in surface soils, while clay provides the majority of charges in subsoil. The total number of negative colloid charges per unit mass is termed the *cation exchange capacity* (CEC), and is dependent on the amount of humus in the soil, and the amount and type of clays present. Kaolinite and other 1:1-type silicate clays and aluminum oxides are low-activity clays, while smectite and vermiculite and other 2:1 clays are high-activity. The CEC of different colloids varies from about 1 to over 200 $cmol_c$/kg and that of whole mineral soils commonly varies from about 1 to 50 $cmol_c$/kg.

The differing ability of soil colloids to adsorb ions and molecules is key to managing soils, both for plant production and to take advantage of how CEC may regulate movement and bio-availability of both nutrients and toxins in the environment. Among the important properties influenced by colloids is the acidity or alkalinity of the soil, the topic of the next chapter.

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STUDY QUESTIONS

1. Describe the *soil colloidal complex*, indicate its various components, and explain how it tends to serve as a "bank" for plant nutrients.
2. How do you account for the difference in surface area associated with a grain of kaolinite clay compared to that of montmorillonite, a smectite?
3. Contrast the difference in crystalline structure among *kaolinite, smectites, fine-grained micas, vermiculites,* and *chlorites.*
4. There are two basic processes by which silicate clays are formed by weathering of primary minerals. Which of these would likely be responsible for the formation of (1) fine-grained mica, and (2) kaolinite from muscovite mica? Explain.
5. If you wanted to find a soil high in kaolinite, where would you go? The same for (1) smectite and (2) vermiculite?
6. Which of the silicate clay minerals would be *most* and *least* desired if one were interested in (1) a good foundation for a building, (2) a high cation exchange capacity, (3) an adequate source of potassium, and (4) a soil on which hard clods form after plowing?
7. Which of the following would you expect to be *most* and *least* sticky and plastic when wet: (1) a soil with significant sodium saturation in a semiarid area, (2) a soil high in exchangeable calcium in a subhumid temperate area, or (3) a well-weathered acid soil in the tropics? Explain your answer.
8. A soil at pH 7.0 contains 4% humus, 10% montmorillonite, 10% vermiculite, and 10% Fe, Al oxides. What is its approximate cation exchange capacity?
9. Calculate the number of grams of Al^{3+} ions needed to replace 10 $cmol_c$ of Ca^{2+} ion from the exchange complex of 1 kg of soil.
10. A soil has been determined to contain the exchangeable cations in these amounts: $Ca^{2+} = 9$ $cmol_c$, $Mg^{2+} = 3$ $cmol_c$, $K^+ = 1$ $cmol_c$, $Al^{3+} = 3$ $cmol_c$. (a) What is the CEC of this soil? (b) What is the aluminum saturation of this soil?
11. A 100 g sample of a soil has been determined to contain the exchangeable cations in these amounts: $Ca^{2+} = 90$ mg, $Mg^{2+} = 35$ mg, $K^+ = 28$ mg, $Al^{3+} = 60$ mg. (a) What is the CEC of this soil? (b) What is the aluminum saturation of this soil?
12. A 100 g sample of a soil was shaken with a strong solution of $BaCl_2$ buffered at pH 8.2. The soil suspension was then filtered, the filtrate was discarded, and the soil was thoroughly leached with distilled water to remove any nonexchangeable Ba^{2+}. Then the sample was shaken with a strong solution of $MgCl_2$ and again filtered. The last filtrate was found to contain 10,520 mg of Mg^{2+} and 258 mg of Ba^{2+}. What is the CEC of the soil?
13. Explain the importance of K_d and K_{oc} in assessing the potential pollution of drainage water. Which of these expressions is likely to be most consistently characteristic of the organic compounds in question regardless of the type of soil involved? Explain.
14. An accident at a nuclear power plant has contaminated soil with strontium-90 (Sr^{2+}), a dangerous radionuclide. Health officials order forages growing in the area to be cut, baled, and destroyed. However, there is concern that as the forage plants regrow, they will take up the strontium from the soil and cows eating this contaminated forage will excrete the strontium into their milk. You are the only soil scientist assigned to a risk assessment team consisting mainly of distinguished physicians and statisticians. Write a brief memo to your colleagues explaining how the properties of the soil in the area, especially those related to cation exchange, could affect the risk of contaminating the milk supply.
15. Explain why there is environmental concern about the adsorption by soil colloids of such normally beneficial substances as antibiotic drugs and natural insecticides.

REFERENCES

Bayer, C., L. Martin-Neto, J. Mielniczuk, C. N. Pillon, and L. Sangoi. 2001. "Changes in soil organic matter fractions under subtropical no-till cropping systems." *Soil Science Society of America Journal* 65:1473–1478.

Bellini, G., M. E. Sumner, D. E. Radcliffe, and N. P. Qafoku. 1996. "Anion transport through columns of highly weathered acid soil: Adsorption and retardation," *Soil Science Society of America Journal* 60:132–137.

Dixon, J. B., and S. B. Weed. 1989. *Minerals in Soil Environments*, 2nd ed. Soil Science Society of America, Madison, WI.

Essington, M. E. 2004. "Cation exchange." *Soil and Water Chemistry: An Integrative Approach*. CRC Press, Boca Raton, FL, pp. 399–444.

Essington, M. E., J. Lee, and Y. Seo. 2010. "Adsorption of antibiotics by montmorillonite and kaolinite." *Soil Science Society of America Journal* 74:1577–1588.

Evangelou, V. P., and R. E. Phillips. 2005. "Cation exchange in soils." In A. Tabatabai and D. Sparks (eds.). *Chemical Processes in Soils*. SSSA Book Series No. 8. Soil Science Society of America, Madison, WI, pp. 343–410.

Hu, H. Q., H. L. Liu, J. Z. He, and Q. Y. Huang. 2007. "Effect of selected organic acids on cadmium sorption by variable- and permanent-charge soils." *Pedosphere* 17:117–123.

Kim, K. R., G. Owens, S. I. Kwon, K. H. So, D. B. Lee, and Y. Ok. 2011. "Occurrence and environmental fate of

FOR REFERENCE PURPOSES ONLY

veterinary antibiotics in the terrestrial environment." *Water, Air, & Soil Pollution* **214**:163–174.

Krishnaswamy, J., and D. D. Richter. 2002. "Properties of advanced weathering-stage soils in tropical forests and pastures." *Soil Science Society of America Journal* **66**:244–253.

Meunier, A. 2005. *Clays*. Springer-Verlag, Berlin, p. 470.

Morra, M. J., M. H. Chaverra, L. M. Dandurand, and C. S. Orser. 1998. "Survival of *Pseudomonas flourescens* 2-79RN$_{10}$ in clay powders undergoing drying." *Soil Science Society of America Journal* **62**:663–670.

Reddy, P. P. 2013. "Disguising the leaf surface." *Recent Advances in Crop Protection*. Springer India, New York, pp. 91–102.

Reid, D. A., and A. L. Ulery. 1998. "Environmental applications of smectites." In J. Dixon, D. Schultze, W. Bleam, and J. Amonette (eds.). *Environmental Soil Mineralogy*. Soil Science Society of America, Madison, WI.

Seabrook, C. 1995. *Red Clay, Pink Cadillacs and White Gold: The Kaolin Chalk War*. Longstreet Press, Atlanta.

Seybold, C. A., and W. Mersie. 1996. "Adsorption and desorption of atrazine, deethylatrazine, deisopropylatrazine, hydroxyatrazine, and metolachlor in two soils in Virginia." *Journal of Environmental Quality* **25**:1179–1185.

Shamshuddin, J., and H. Ismail. 1995. "Reactions of ground magnesium limestone and gypsum in soils with variable-charged minerals." *Soil Science Society of America Journal* **59**:106–112.

S.K.B. 2004. "Final repository—properties of the buffer." Svensk Kãrnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company). http://www.skb.se/templates/SKBPage_8776.aspx (posted 27 April 2004; verified 24 April 2006).

Stotzky, G. 2000. "Persistence and biological activity in soil of insecticidal proteins from *Bacillus thuringiensis* and of bacterial DNA bound on clays and humic acids." *Journal of Environmental Quality* **29**:691–705.

Sullivan, T. J., I. J. Fernandez, A. T. Herlihy, C. T. Driscoll, T. C. Mcdonnell, N. A. Nowicki, K. U. Snyder, and J. W. Sutherland. 2006. "Acid-base characteristics of soils in the Adirondack Mountains, New York." *Soil Science Society of America Journal* **70**:141–152.

Swedish Nuclear Power Inspectorate. 2005. "Engineered barrier system-long-term stability of buffer and backfill." Report from a workshop in Lund, Sweden, 15–17 November, 2004, synthesis and extended abstracts. Swedish Nuclear Power Inspectorate. *SKI Research Report*, 48, 120.

Tice, K. R., R. C. Graham, and H. B. Wood. 1996. "Transformations of 2:1 phyllosilicates in 41-year-old soils under oak and pine." *Geoderma* **70**:49–62.

Waegeneers, N., E. Smolders, and R. Merckx. 1999. "A statistical approach for estimating radiocesium interception potential of soils." *Journal of Environmental Quality* **28**:1005–1011.

Way, J. T. 1850. "On the power of soils to absorb manure." *Journal of the Royal Agricultural Society of England* **11**:313–379.

Weil, R. R. 2015. *Laboratory Manual for Introductory Soils*, 9th ed. Kendall/Hunt, Dubuque, IA.

Windham, B. 2007. "'White dirt' is part of culture, commerce." TuscaloosaNews.com, Tuscaloosa, AL. http://www.tuscaloosanews.com/article/20071028/news/710280337?p=1&tc=pg

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9 Soil Acidity

An acid-soil community. (Ray R. Weil)

What have they done to the rain?
—*Song by* Malvina Reynolds

The degree of soil acidity or alkalinity, expressed as pH, is a *master variable* that affects a wide range of soil chemical and biological properties. This chemical variable greatly influences the likelihood that plant roots will take up both nutrient and toxic elements. Soil pH also has pronounced impacts on communities of soil microorganisms and their activities. The mix of plant species that dominate a landscape under natural conditions often reflects the pH of the soil. For people attempting to produce crops or ornamental plants, soil pH is a major determinant of which species will grow well or even grow at all in a given site.

Soil pH affects the *mobility* of many pollutants in soil by influencing the rate of their biochemical breakdown, their solubility, and their adsorption to colloids. Thus, soil pH is a critical factor in predicting the likelihood that a given pollutant will contaminate groundwater, surface water, and food chains. Furthermore, there are certain situations in which so much acidity is generated that the acid itself becomes a significant environmental pollutant. For example, soils on certain types of disturbed land generate extremely acid drainage water that can cause massive fish kills when it reaches a lake or stream.

Many complex factors affect soil pH, but none more than two simple balances: the balance between acid and nonacid cations on colloid surfaces and the balance between H^+ and OH^- ions in the soil solution. These balances, in turn, are largely controlled by the nature of the soil colloids. Therefore, to understand and manage soil acidity, it is essential to have a good grasp of the concepts of charged colloidal surfaces and cation exchange as presented in Chapter 8. Also inextricably tied to soil acidity is the toxicity of the nonnutrient element, **aluminum**.

Acidification is a natural process involved in soil formation. It reaches its greatest expression in humid regions where rainfall is sufficient to thoroughly leach the soil profile. Not surprisingly, acidity is one of the main constraints to crop production in these areas. Forests, which comprise the natural vegetation in most humid regions, are generally better adapted to acid soils than are most crops. Nonetheless, forest health has declined where soils are incapable of resisting the effects of human-induced acidification.

By contrast, leaching is much less extensive in drier regions, allowing soils to retain enough nonacid Ca^{2+}, Mg^{2+}, K^+, and Na^+ to prevent a buildup of acid cations. Soils in semiarid and arid regions, therefore, tend to have **alkaline** pH levels (i.e., pH > 7), sometimes accompanied by high levels of soluble salts and exchangeable sodium, soil conditions that will be discussed in Chapter 10. In this chapter we will focus on acid soils, those with pH levels well below 7.

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9.1 WHAT PROCESSES CAUSE SOIL ACIDIFICATION?

Acidity and alkalinity are usually quantified using the pH scale, which expresses the activity or concentration of H^+ ions present in a solution. Therefore, before we begin our discussion of the chemical nature and causes of acidity in soils, it will be useful to review the fundamentals about pH in Box 9.1. It will also be of value to develop a feel for the range of pH values found in soils and to compare these to the pH values of other common substances (see Figure 9.2).

In order to understand soil acidification and its management, we need to know where the H^+ ions come from, how they enter the soil system, and how they may be lost. We will begin by describing a variety of processes that add H^+ ions to the soil system and therefore contribute to acidification. Although most of these acid-producing processes occur naturally, human activities have a major impact on some of them, as we shall see in Section 9.6.

BOX 9.1

SOIL PH, SOIL ACIDITY, AND ALKALINITY

Whether a soil is acid, neutral, or alkaline is determined by the comparative concentrations of H^+ and OH^- ions.[a] Pure water provides these ions in equal concentrations:

$$H_2O \rightleftharpoons H^+ + OH^-$$

The equilibrium for this reaction is far to the left; only about 1 out of every 10 million water molecules is dissociated into H^+ and OH^- ions. The ion product of the concentrations of the H^+ and OH^- ions is a constant (K_w), which at 25 °C is known to be 1×10^{-14}:

$$[H^+] \times [OH^-] = K_w = 10^{-14}$$

Since in pure water the concentration of H ions $[H^+]$ must be equal to that of OH^- ions $[OH^-]$, this equation shows that the concentration of each is 10^{-7} ($10^{-7} \times 10^{-7} = 10^{-14}$). It also shows the inverse relationship between the concentrations of these two ions (Figure 9.1). As one increases, the other must decrease proportionately.

Scientists have simplified the means of expressing the very small concentrations of H^+ and OH^- ions by using the *negative logarithm of the H^+ ion concentration,* termed the *pH*. Thus, if the H^+ concentration in an acid medium is 10^{-5}, the pH is 5; if it is 10^{-9} in an alkaline medium, the pH is 9. This logarithmic nature of the pH scale has two important consequences. First, every one unit step down the pH scale represents a tenfold change in acidity. Thus a solution at pH 5.0 has ten times as many H^+ ions as one at pH 6.0 and 100 times as many as one at pH 7.0. Second, keep in mind that much more acidity (H^+ ions) is involved in a *change* of 1 pH unit near the low end of the scale compared to a 1 unit change at the high end. For example, a change from pH 4 to 3 increases the H^+ concentration by 900 micromol/L (from 100 to 1000 micomol H^+/L) while a change from pH 8 to 7 increases the H^+ concentration by only 0.009 micromol (H^+)/L (from 0.001 to 0.01 mmol H^+/L).

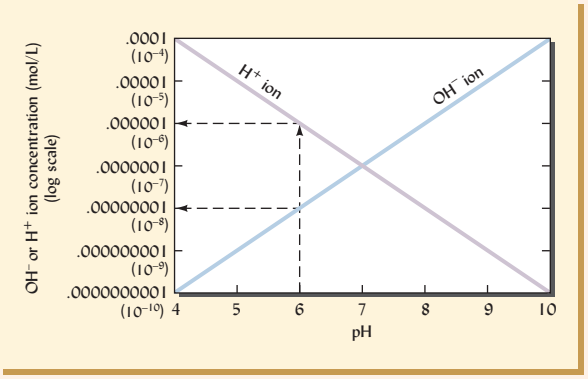

Figure 9.1 *The relationship between pH, pOH, and the concentrations of hydrogen and hydroxyl ions in water solution.*

The pH also gives us an indirect measure of the OH^- ion concentration (the negative logarithm of which is the pOH) since the product of $[H^+] \times [OH^-]$ must always equal 10^{-14}. For example, at pH 5 the $[OH^-]$ is 10^{-9} ($10^{-5} \times 10^{-9} = 10^{-14}$) and the pOH = 9.

Figure 9.1 above shows the relationship between pH and the concentrations of H^+ and OH^- ions. Note that as one goes down, the other goes up, and vice versa. The dotted line illustrates the concentrations of these two ions at pH = 6.0: $[H^+] = 10^{-6}$; $[OH^-] = 10^{-8}$. This reciprocal relationship between H^+ and OH^- ions should always be kept in mind in studying soil acidity and alkalinity.

[a]Technically speaking, chemical reactions are influenced by the activity of an ion rather than by its concentration. This is because of the electrostatic effect of one ion on the activity of other ions nearby. Ionic activities are thus essentially effective concentrations. In soil solutions with low ionic strength the difference between ionic activity and concentration in soils is not very large, so we will use the term *concentration* in this text.

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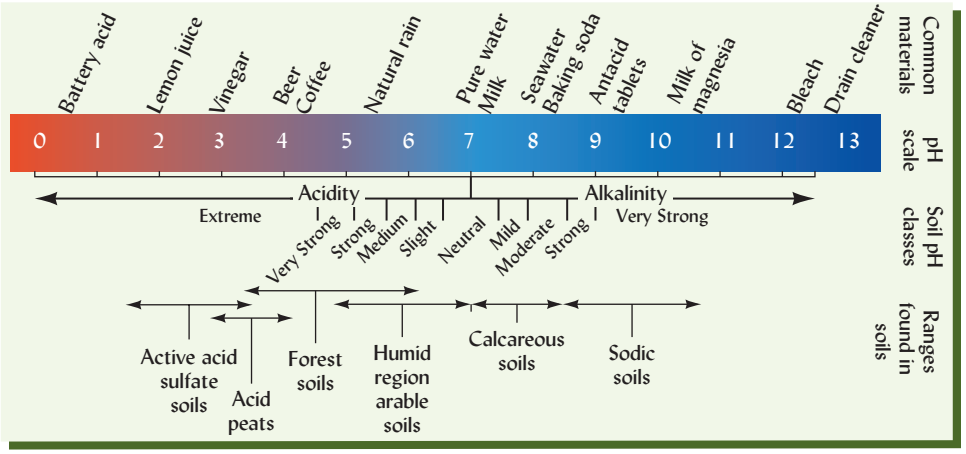

Figure 9.2 *Some pH values for familiar substances (top) compared to terms used to describe soil acidity or alkalinity and ranges of pH typical for various types of soils (bottom).*

Sources of Hydrogen Ions

Carbonic and Other Organic Acids. Perhaps the most ubiquitous contributor to soil acidity is the formation of **carbonic acid** and the subsequent dissociation of its H^+ ions. This weak acid is formed when carbon dioxide gas dissolves in water. Root respiration and the decomposition of soil organic matter by microorganisms produce high levels of CO_2 in soil air, pushing the following reaction to the right:

$$CO_2 + H_2O \longrightarrow H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \qquad pK_a = 6.35 \tag{9.1}$$

Because H_2CO_3 is a weak acid (has a relatively high p*Ka*),[1] its contribution of H^+ ions is negligible when the pH is much below 5.0.

Microbes generate many other organic acids as they break down organic matter in the soil. Some of these are low molecular weight organic acids, such as citric or malic acids, that only weakly dissociate. Others are more complex and stronger acids, such as the carboxylic and phenolic acid groups in humus produced by litter breakdown. A generalized reaction showing a carboxylic group is given:

$$\underset{\text{Organic matter (generalized)}}{[RCH_2OH\ldots]} + O_2 + H_2O \rightleftharpoons \underset{\text{Strong organic acids}}{RCOOH} \rightleftharpoons RCOO^- + H^+ \qquad pK_a = 3 \text{ to } 5 \tag{9.2}$$

The pK_a of carboxylic groups ranges from 3 to 5, depending on the nature of the associated organic structures (R). Other organic groups, such as phenolic (R–OH), dissociate at higher pH levels.

Accumulation of Organic Matter. The accumulation of organic matter tends to acidify the soil for two reasons. First, organic matter forms soluble complexes with nonacid nutrient cations such as Ca^{2+} and Mg^{2+}, thus facilitating the loss of these cations by leaching. Second, organic matter is a source of H^+ ions because it contains numerous acid **functional groups** from which these ions can dissociate. Different groups dissociate at different pH levels. If pH is increased, more functional groups undergo dissociation of H^+ ions, leaving behind an increasing number of negatively charged sites on the molecule. It is these *pH-dependent* negative charges that give rise to the large cation exchange capacity (CEC) for which soil organic matter is well known (see Sections 8.4 and 8.6).

Oxidation of Nitrogen (Nitrification). Oxidation reactions generally produce H^+ ions as one of their products. Reduction reactions, on the other hand, tend to consume H^+ ions and

[1]The pK_a is the negative logarithm (analogous to the pH) of the equilibrium constant for a dissociation reaction—for example, $[H^+] \times [HCO_3^-]/[H_2CO_3] = K_a$. It indicates the pH at which one-half of the acid will be dissociated. Dissociation of the acid can usually be considered negligible when the pH is more than 1.0–2.0 units lower than the pK_a.

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raise soil pH. Ammonium ions (NH_4^+) from organic matter or from most fertilizers are subject to microbial oxidation that converts the N to nitrate ions (NO_3^-). The reaction with oxygen, termed nitrification, releases two H^+ ions for each NH_4^+ ion oxidized (see also Section 13.7). Because the NO_3^- produced is the anion of a **strong acid** (nitric acid, HNO_3), it does *not* tend to recombine with the H^+ ion to make the reaction go to the left

$$NH_4^+ + 2O_2 \rightleftharpoons H_2O + H^+ + \underbrace{H^+ + NO_3^-}_{\text{Dissociated nitric acid}} \tag{9.3}$$

Oxidation of Sulfur. The decomposition of plant residues commonly involves the oxidation of organic –SH groups to yield sulfuric acid (H_2SO_4). Another important source of this strong acid is the oxidation of reduced sulfur in minerals such as pyrite. This and related reactions are responsible for producing large amounts of acidity in certain soils in which reduced sulfur is plentiful and oxygen levels are increased by drainage or excavation (see Section 9.6)

$$\underset{\text{Pyrite}}{FeS_2} + 3\tfrac{1}{2}O_2 + H_2O \rightleftharpoons \underset{\text{Ferrous sulfate}}{FeSO_4} + \underbrace{2H^+ + SO_4^{2-}}_{\text{Dissociated sulfuric acid}} \tag{9.4}$$

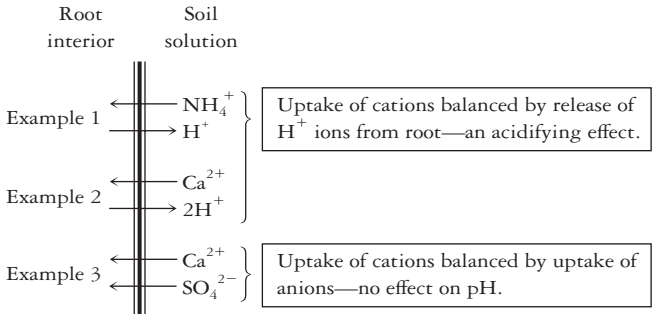
Acids in Precipitation. Rain, snow, fog, and dust contain a variety of acids that contribute H^+ ions to the soil receiving the precipitation. As raindrops fall through unpolluted air, they dissolve CO_2 and form enough carbonic acid to lower the pH of the water from 7.0 (the pH of pure water) to about 5.6. Varying amounts of sulfuric and nitric acids form in precipitation from certain sulfur and nitrogen gases produced by lightning, volcanic eruptions, forest fires, and the combustion of fossil fuels. Unlike carbonic acid, these strong acids completely dissociate to form H^+ ions and sulfate or nitrate anions:

$$H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+ \tag{9.5}$$

$$HNO_3 \rightleftharpoons NO_3^- + H^+ \tag{9.6}$$

Downwind from industrial areas, combustion of coal and petroleum products has significantly increased the amounts of these strong acids found in precipitation (see Section 9.6).

Plant Uptake of Cations. Plant roots affect pH. For every positive charge taken in as a cation, a root can maintain charge balance either by taking up a negative charge as an anion or by exuding a positive charge as a different cation. When they take up far more of certain cations (e.g., K^+, NH_4^+, and Ca^{2+}) than they do of anions (e.g., NO_3^-, SO_4^{2-}), plants usually exude H^+ ions into the soil solution to maintain charge balance. In the first two of the following examples, plant nutrient uptake results in the addition of H^+ ions to the soil solution:



(9.7)

Balance Between Production and Consumption of H^+ Ions

The H^+ ion-producing processes just discussed combine to stimulate soil acidification. However, the degree of acidification that actually occurs in a given soil is determined by the

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Table 9.1
THE MAIN PROCESSES THAT PRODUCE OR CONSUME HYDROGEN IONS (H^+) IN SOIL SYSTEMS
Production of H^+ ions increases soil acidity, while consumption of H^+ ions delays acidification and leads to alkalinity. The pH level of a soil reflects the long-term balance between these two types of processes.

Acidifying (H^+ ion–producing) processes	Alkalinizing (H^+ ion–consuming) processes
Formation of carbonic acid from CO_2	Input of bicarbonates or carbonates
Acid dissociation such as:	Anion protonation such as:
$RCOOH \rightarrow RCOO^- + \mathbf{H}^+$	$RCOO^- + \mathbf{H}^+ \rightarrow RCOOH$
Oxidation of N, S, and Fe compounds	Reduction of N, S, and Fe compounds
Atmospheric H_2SO_4 and HNO_3 deposition	Atmospheric Ca, Mg deposition
Cation uptake by plants	Anion uptake by plants
Accumulation of acidic organic matter	Specific (inner sphere) adsorption of anions (especially SO_4^{2-})
Cation precipitation such as:	Cation weathering from minerals such as:
$Al^{3+} + 3H_2O \rightarrow 3\mathbf{H}^+ + Al(OH)_3^0$	$3\mathbf{H}^+ + Al(OH)_3^0 \rightarrow Al^{3+} + 3H_2O$
$SiO_2 + 2Al(OH)_3 + Ca^{2+} \rightarrow CaAl_2SiO_6 + 2H_2O + 2\mathbf{H}^+$	$CaAl_2SiO_6 + 2H_2O + 2\mathbf{H}^+ \rightarrow SiO_2 + 2Al(OH)_3 + Ca^{2+}$
Deprotonation of pH-dependent charges	Protonation of pH-dependent charges

balance between those processes that produce H^+ ions and other processes that *consume* them (Table 9.1). An example of the latter is the case in which plant uptake of an anion such as NO_3^- exceeds the uptake of associated cations. In this case, the root exudes the anion, bicarbonate (HCO_3^-), to maintain charge balance. The increase in the concentration of bicarbonate ions tends to reverse the dissociation of carbonic acid (see Eq. [9.1]), and thereby *consume* H^+ ions and raise the pH of the soil solution

Root interior | Soil solution

$$\left.\begin{array}{l} \leftarrow NO_3^- \\ \rightarrow HCO_3^- \end{array}\right\} \boxed{\text{Uptake of anion balanced by release of bicarbonate ion—alkalizing effect.}} \qquad (9.8)$$

Another H^+ ion–consuming process involving nitrogen is the reduction of nitrate to nitrogen gases under anaerobic conditions (see denitrification, Sections 7.3 and 13.9).

The weathering of nonacid cations from minerals (Section 2.1) is a slow but very important H^+ ion–consuming process that counteracts acidification. An example is the weathering of calcium from a silicate mineral:

$$\text{Ca-silicate} + 2H^+ \longrightarrow H_4SiO_4 + Ca^{2+} \qquad (9.9)$$

Some of the nonacid cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) so released become exchangeable cations on the soil colloids. Hydrogen ions added to the soil solution from acids in rain (and other sources just discussed) may replace these cations on the cation exchange sites of humus and clay. The displaced nonacid cations are then subject to loss by leaching along with the anions of the added acids (Figure 9.3). The soil slowly becomes more acid if the leaching of Ca^{2+}, Mg^{2+}, K^+, and Na^+ proceeds faster than the release of these cations from weathering minerals. Thus, the formation of acid soils is favored by high rainfall, parent materials low in Ca, Mg, K, and Na, and a high degree of biological activity (favoring formation of H_2CO_3). The positive relationship between annual rainfall and soil acidity is well documented and largely accounts for the global distribution of acid and alkaline soils (Figure 9.4).

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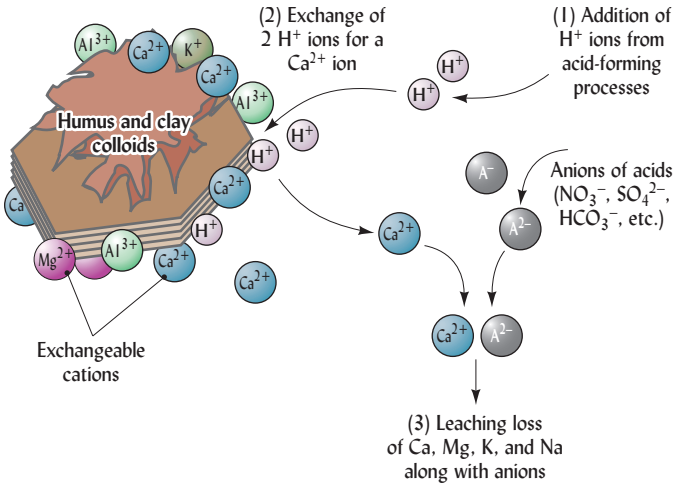


Figure 9.3 *Soils become acid when H^+ ions added to the soil solution exchange with nonacid Ca^{2+}, Mg^{2+}, K^+, and Na^+ ions held on humus and clay colloids. The nonacid cations can then be exported in leaching water along with accompanying anions. As a result, the exchange complex (and therefore also the soil solution) becomes increasingly dominated by acid cations (H^+ and Al^{3+}). Because of this sequence of events, H^+ ion–producing processes acidify soils in humid regions where leaching is extensive, but cause little long-term soil acidification in arid regions where the Ca^{2+}, Mg^{2+}, K^+, and Na^+ are mostly not removed by leaching. In the latter case, the Ca^{2+}, Mg^{2+}, K^+, and Na^+ remain in the soil and reexchange with the acid cations, preventing a drop in pH level.* (Diagram courtesy of Ray R. Weil)

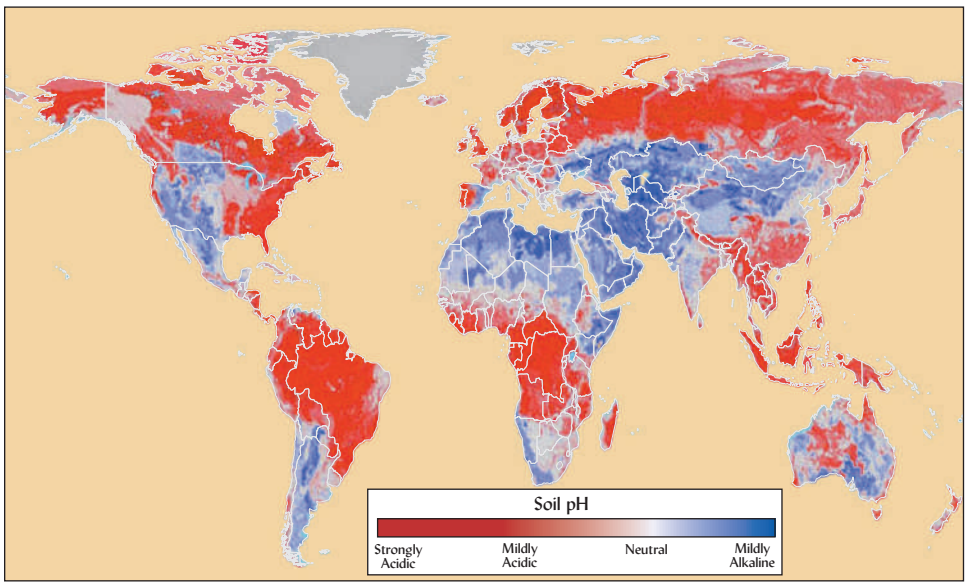
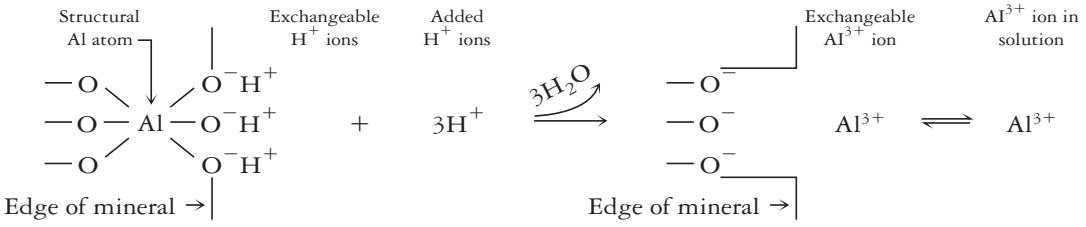


Figure 9.4 *The global distribution of soil acidity and alkalinity is largely related to annual rainfall and its excess over evapotranspiration. Except for the frozen artic regions, the distribution of acid soils (red areas on the map) corresponds quite closely to the distribution of forest vegetation.* [Map based on data from IGBP-DIS (2000). (Used by permission of The Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin-Madison)]

9.2 ROLE OF ALUMINUM IN SOIL ACIDITY

Although low pH is defined as a high concentration of H^+ ions, **aluminum** also plays a central role in soil acidity. Aluminum is a major constituent of most soil minerals (aluminosilicates and aluminum oxides), including clays. When H^+ ions are adsorbed on a clay surface, they usually do not remain as exchangeable cations for long, but instead they attack the structure of the minerals, releasing Al^{3+} ions in the process. The Al^{3+} ions then become adsorbed on the colloid's cation-exchange sites. These exchangeable Al^{3+} ions, in turn, are in equilibrium with dissolved Al^{3+} in the soil solution:



(9.10)

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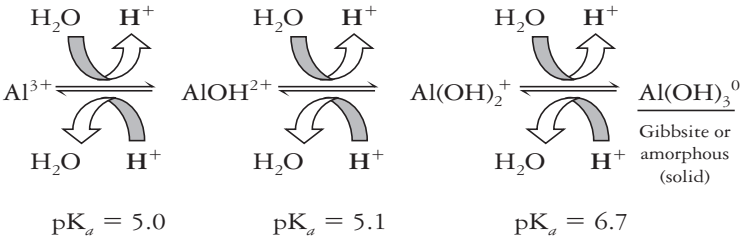
The exchangeable and soluble Al^{3+} ions play two critical roles in the soil acidity story. First, aluminum is *highly toxic* to most organisms and is responsible for much of the deleterious impact of soil acidity on plants and aquatic animals. We will discuss this role in Section 9.7.

Second, Al^{3+} ions have a strong tendency to hydrolyze, splitting water molecules into H^+ and OH^- ions.[2] The aluminum combines with the OH^- ions, leaving the H^+ to lower the pH of the soil solution. For this reason, Al^{3+} and H^+ together are considered **acid cations**. A single Al^{3+} ion can thus release up to three H^+ ions as the following reversible reaction series proceeds to the right in stepwise fashion:



(9.11)

Most of the hydroxy aluminum ions $[Al(OH)x^{y+}]$ formed as the pH increases are strongly adsorbed to clay surfaces or complexed with organic matter. Often the hydroxy aluminum ions join together, forming large polymers with many positive charges. When tightly bound to the colloid's negative charge sites, these polymers are not exchangeable and so mask much of the colloid's potential cation exchange capacity. As the pH is raised and more of the hydroxyl aluminum ions precipitate as uncharged $Al(OH)_3^0$, the negative sites on the colloids become available for cation exchange. This is one reason for the increase in soil CEC as the pH is raised from 4.5 to 7.0 (at which pH virtually all the aluminum cations have precipitated as $Al(OH)_3^0$).

9.3 POOLS OF SOIL ACIDITY

Principal Pools of Soil Acidity

Research suggests that three major pools of acidity are common in soils: (1) **active acidity** due to the H^+ ions in the soil solution; (2) **salt-replaceable (exchangeable) acidity**, involving the aluminum and hydrogen that are *easily exchangeable* by other cations in a simple unbuffered salt solution, such as KCl; and (3) **residual acidity**, which can be neutralized by limestone or other alkaline materials but cannot be detected by the salt replacement. These types of acidity all add up to the **total acidity** of a soil. In addition, a much less common, but sometimes very important fourth pool, namely, **potential acidity**, can arise upon the oxidation of sulfur compounds in certain acid sulfate soils (see Section 9.6).

Active Acidity. The active acidity pool is defined by the H^+ ion activity in the soil solution. This pool is very small compared to the acidity in the exchangeable and residual pools. For example, only about 2 kg of calcium carbonate are needed to neutralize the active acidity in the upper 15 cm of a hectare of an average mineral soil at pH 4 and 20% moisture. Even so, the active acidity is extremely important, since it determines the solubility of many substances and provides the soil solution environment to which plant roots and microbes are exposed. Very acid soils contain aluminum ions in solution, which can add to the active acidity as they hydrolyze.

Exchangeable (Salt-Replaceable) Acidity. Salt-replaceable acidity is primarily associated with exchangeable aluminum and hydrogen ions that are present in large quantities in very

[2]Iron (Fe^{3+}) has properties similar to those of aluminum, undergoes similar reactions, and can also produce H^+ ions by hydrolysis. However, because Fe^{3+} hydrolyzes at pH levels (<3.0) that are below those commonly encountered in soils, we will confine our discussion to aluminum.

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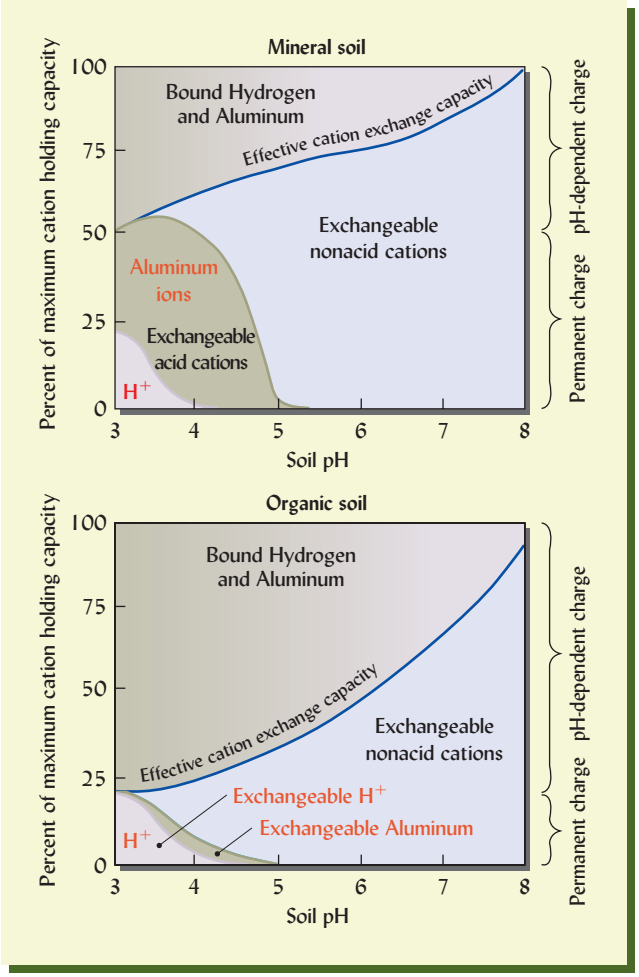

Figure 9.5 *General relationships between soil pH and cations held in exchangeable form or tightly bound to colloids in a mineral and an organic soil. Note that any particular soil would give somewhat different distributions. (Upper) A mineral soil with mixed mineralogy and a moderate organic matter level exhibits a moderate decrease in effective cation exchange capacity as pH is lowered, suggesting that* pH-dependent charges *and* permanent charges*(see Section 8.6 for explanation of these terms) each account for about half of the maximum CEC. At pH values above 5.5, the concentrations of exchangeable aluminum and H^+ ions are negligible, and the effective CEC is essentially 100% saturated with exchangeable nonacid cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+, the so-called base cations). As pH drops from 7.0 to about 5.5, the effective CEC is reduced because H^+ ions and $Al(OH)_x^{y+}$ ions (which may include $AlOH^{2+}$, $Al(OH)_2^+$, etc.) are tightly bound to some of the pH-dependent charge sites. As pH is further reduced from 5.5 to 4.0, aluminum ions (especially Al^{3+}), along with some H^+ ions, occupy an increasing portion of the remaining exchange sites. Exchangeable H^+ ions occupy a major portion of the exchange complex only at pH levels below 4.0. (Lower) The CEC of an organic soil is dominated by pH-dependent (variable) charges with only a small amount of permanent charge. Therefore, as pH is lowered, the effective CEC drops more dramatically in the organic soil than in the mineral soil. At low pH levels, exchangeable H^+ ions are more prominent and Al^{3+} less prominent on the organic soil than on the mineral soil.* (Diagram courtesy of Ray R. Weil)

acid soils (see Figure 9.5). These ions can be released into the soil solution by cation exchange with an unbuffered salt, such as KCl

$$\underset{\text{(soil solid)}}{\text{Clay}\begin{matrix}- \\ - \\ - \\ -\end{matrix}\begin{matrix}Al^{3+} \\ \\ \\ H^+\end{matrix}} + \underset{\text{(soil solution)}}{4KCl} \rightleftharpoons \underset{\text{(soil solid)}}{\text{Clay}\begin{matrix}- \\ - \\ - \\ -\end{matrix}\begin{matrix}K^+ \\ K^+ \\ K^+ \\ K^+\end{matrix}} + \underset{\text{(soil solution)}}{AlCl_3 + HCl} \qquad (9.12)$$

Once released to the soil solution, the aluminum hydrolyzes to form additional H^+, as explained in Section 9.2. The chemical equivalent of salt-replaceable acidity in strongly acid soils is commonly thousands of times that of active acidity in the soil solution. Even in moderately acid soils, the limestone needed to neutralize this type of acidity is commonly more than 100 times that needed to neutralize the soil solution (active acidity). At a given pH value, exchangeable acidity is generally highest soils whose clay fraction is dominated by smectites, intermediate for vermiculites, and lowest for kaolinite.

Residual Acidity. Together, exchangeable (salt-replaceable) and active acidity account for only a fraction of the total soil acidity. The remaining **residual acidity** is generally associated with hydrogen and aluminum ions (including the aluminum hydroxy ions) that are bound in nonexchangeable forms by organic matter and clays (see Figure 9.5). As the pH increases, the bound hydrogen dissociates and the bound aluminum ions are released and precipitate

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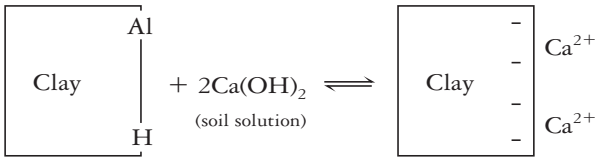
as amorphous $Al(OH)_3^0$. These changes free up negatively charged cation exchange sites and increase the cation exchange capacity. The reaction with a liming material [e.g., $Ca(OH)_2$] shows how the bound hydrogen and aluminum can be released



$$\text{Clay}\!\!-\!\!\text{Al}\!\!-\!\!\text{H} + 2Ca(OH)_2 \rightleftharpoons \text{Clay}\!\!-\!\!Ca^{2+}\;\; -\!\!Ca^{2+} + Al(OH)_3 + H_2O \qquad (9.13)$$

The residual acidity is commonly far greater than either the active or salt-replaceable acidity. It may be 1000 times greater than the soil solution or active acidity in a sandy soil and 50,000 or even 100,000 times greater in a clayey soil high in organic matter. The amount of ground limestone recommended to at least partly neutralize residual acidity in the upper 15 cm of a strongly acid soil may be at least 5–10 metric tons (Mg) per hectare (2.25–4.5 tons per acre).

Total Acidity. For most soils (not potential acid sulfate soils) the total acidity that must be overcome to raise the soil pH to a desired value can be defined as:

$$\text{Total acidity} = \text{active acidity} + \text{salt-replaceable acidity} + \text{residual acidity} \qquad (9.14)$$

We can conclude that the pH of the soil solution is only the tip of the iceberg in determining how much lime may be needed to overcome effects of soil acidity.

Soil pH and Cation Associations

Exchangeable and Bound Cations. Figure 9.5 illustrates the relationship between soil pH and the prevalence of various exchangeable and tightly bound cations in a mineral and an organic soil. Two forms of hydrogen and aluminum are shown in Figure 9.5: (1) that tightly held by the pH-dependent sites (*bound*), and (2) that associated with negative charges on the colloids (*exchangeable*). The bound forms contribute to the residual acidity pool, but only the exchangeable ions have an immediate effect on soil pH. As we shall see later, both forms are very much involved in determining how much lime or sulfur is needed to change soil pH (see Section 9.8).

Effective CEC and PH. Note that in both soils illustrated in Figure 9.5, the effective CEC increases as the pH level rises. This change in effective CEC results mainly from two factors: (1) the binding and release of H^+ ions on pH-dependent charge sites (as explained in Section 8.6), and (2) the hydrolysis reactions of aluminum species (as explained in Section 9.2). The change in effective CEC will be most dramatic for organic soils (Figure 9.5, *lower*) and highly weathered mineral soils dominated by iron and aluminum oxide clays. However, effective CEC changes with pH even in surface soils dominated by 2:1 clays, which carry mainly permanent charges. This is because a substantial amount of variable charge is usually supplied by the organic matter and the weathered edges of clay minerals.

Cation Saturation Percentages

The proportion of the CEC occupied by a given ion is termed its **saturation percentage**. Consider a soil with a CEC of 20 $cmol_c$/kg holding these amounts of exchangeable cations (in $cmol_c$/kg): 10 of Ca^{2+}, 3 of Mg^{2+}, 1 of K^+, 1 of Na^+, 1 of H^+, and 4 of Al^{3+}. This soil with 10 $cmol_c$ Ca^{2+}/kg and a CEC of 20 $cmol_c$/kg is said to be 50% calcium saturated. Likewise, the aluminum saturation of this soil is 20% (4/20 = 0.20 or 20%). Together, the 4 $cmol_c$/kg of exchangeable Al^{3+} and 1 $cmol_c$/kg of exchangeable H^+ ions give this soil an **acid saturation** of 25% [(4 + 1)/20 = 0.25]. Similarly, the term **nonacid saturation** can be used to refer to the proportion of Ca^{2+}, Mg^{2+}, K^+, Na^+, etc., on the CEC. Thus, the soil in our example has a nonacid saturation of 75% [(10 + 3 + 1 + 1)/20 = 0.75].

Traditionally, the nonacid cations have been referred to as "base" cations and their proportion on the CEC the **percent "base" saturation**. Cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+

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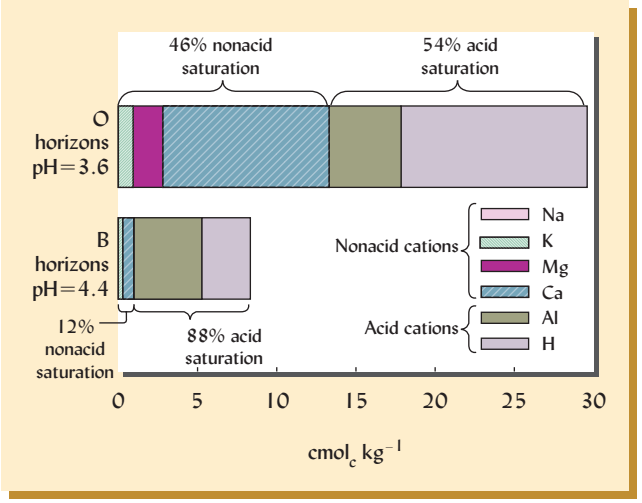

Figure 9.6 *Saturation of the exchange capacity with acid and nonacid cations helps characterize the acidification of soils in the Adirondack Mountains of New York, USA. The data represent the averages for O horizons and B horizons from more than 150 pedons in 144 watersheds. From the graph we can see that the effective cation exchange capacity (ECEC), the sum of all the exchangeable cations, was almost 30 cmol$_c$/kg in the O horizons compared to only about 8 cmol$_c$/kg in the B horizons. As is typical of temperate forested soils, the O horizons (which were about 90% organic) exhibited an extremely acid pH but a relatively low acid saturation, and the acid cations were mainly H^+. By contrast, the B horizons (which were about 90% mineral) had a more moderate pH but were 88% acid-saturated, and most of the acid cations were aluminum.* [Modified from Sullivan et al. (2006)]

do not hydrolyze as Al^{3+} and Fe^{3+} do, and therefore are not acid-forming cations. However, they are also *not* bases and do not necessarily form bases in the chemical sense of the word.[3] Because of this ambiguity, it is more straightforward to refer to *acid saturation* when describing the degree of acidity on the soil cation exchange complex. Figure 9.6 uses these concepts to characterize acidified soil in the Adirondack Mountains of New York, USA. The relationships among these terms can be summarized as follows:

$$\text{Percent acid saturation} = \frac{\text{cmol}_c \text{ of exchangeable } Al^{3+} + H^+}{\text{cmol}_c \text{ of CEC}} \tag{9.15}$$

$$\begin{aligned}\text{Percent nonacid saturation} = \text{Percent "base" saturation} &= \frac{\text{cmol}_c \text{ of exchangeable } Ca^{2+} + Mg^{2+} + K^+ + Na^+}{\text{cmol}_c \text{ of CEC}} \\ &= 100 - \frac{\text{percent acid}}{\text{saturation}}\end{aligned} \tag{9.16}$$

Acid (or Nonacid) Cation Saturation and pH

The percentage saturation of a particular cation (e.g., Al^{3+} or Ca^{2+}) or class of cations (e.g., nonacid cations or acid cations) is often more closely related to the nature of the soil solution than is the absolute amount of these cations present. Generally, as illustrated in Figure 9.7, when the acid cation percentage increases, the pH of the soil solution decreases. However, a number of factors can modify this relationship.

Effect of Type of Colloid. The type of clay minerals or organic matter present influences the pH of different soils at the same percent acid saturation. This is due to differences in the ability of various colloids to furnish H^+ ions to the soil solution. For example, the dissociation of adsorbed H^+ ions from smectites is much higher than that from Fe and Al oxide clays. Consequently, the pH of soils dominated by smectites is appreciably lower than that of the oxides at the same percent acid saturation. The dissociation of adsorbed hydrogen from 1:1-type silicate clays and organic matter is intermediate between that from smectites and from the hydrous oxides.

Effect of Kind of Adsorbed Nonacid Cations. The relative amounts of each of the nonacid cations present on the colloidal complex is another factor influencing soil pH. For ex-

[3]A base is a substance that combines with H^+ ions, while an acid is a substance that releases H^+ ions. The anions OH^- and HCO_3^- are strong bases because they react with H^+ to form the weak acids, H_2O and H_2CO_3, respectively.

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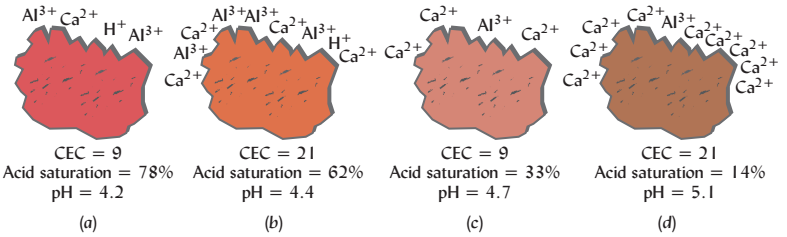

Figure 9.7 *Acid cation saturation and soil pH in four hypothetical soils, two with a high CEC and two with a low CEC. The relative proportion of the effective CEC occupied by Al^{3+} and H^+ (the percent acid saturation) is more closely related to the soil pH than is the absolute amount of these acid cations present. Thus, the pH can be seen to increase from left to right as the percent acid saturation decreases, regardless of changes in the cation exchange capacity. For example, even though soil (b) has about twice as many mol_c of acid cations, soil (a) has a lower pH because it has a higher percent acid saturation.* (Diagram courtesy of Ray R. Weil)

ample, soils with high sodium saturation (usually highly alkaline soils of arid and semiarid regions) have much higher pH values than those dominated by calcium and magnesium (as explained in Section 10.1).

Effect of Method of Measuring CEC. An unfortunate ambiguity in the cation saturation percentage concept is that the actual percentage calculated depends on whether the effective CEC (which itself changes with pH) or the maximum potential CEC (which is a constant for a given soil) is used in the denominator. The different methods of measuring CEC are explained in Section 8.12.

When the concept of cation saturation was first developed, the percent nonacid saturation (then termed "base saturation") was calculated by dividing the level of these exchangeable cations by the *potential* cation exchange capacity that is measured at high pH values (7.0 or 8.2). Thus, if a representative mineral soil such as shown in Figure 9.5 has a potential CEC of 20 $cmol_c$/kg, and at pH 6 has a nonacid exchangeable cation level of 15 $cmol_c$/kg, the percent nonacid cation saturation would be calculated as 15 $cmol_c$/20 $cmol_c \times 100 = 75\%$. The percent "base" saturation determined by this method is still used as a soil classification criterion in *Soil Taxonomy.*

A second method relates the exchangeable cation levels to the *effective* CEC at the pH of the soil. As Figure 9.5 shows, the effective CEC of the representative soil at pH 6 would be only about 15 $cmol_c$/kg. At this pH level, essentially all the exchangeable sites are occupied by nonacid cations (15 $cmol_c$/kg). Using the effective CEC as our base, we find that the nonacid cation saturation is 15 $cmol_c$/15 $cmol_c \times 100 = 100\%$. Thus, this soil at pH 6 is either 75% or 100% saturated with nonacid cations, depending on whether we use the potential CEC or the effective CEC in our calculations.

Uses of Cation Saturation Percentages. Which nonacid saturation percentage just described is the correct one? It depends on the purpose at hand. The first percentage (75% of the potential CEC) indicates that significant acidification has occurred and is used in soil classification (e.g., by definition Ultisols must have a nonacid or "base" saturation of less than 35%). The second percentage (100% of the effective CEC) is more relevant to soil fertility and the availability of nutrients. It indicates what proportion of the total exchangeable cations at a given soil pH is accounted for by nonacid cations. For example, when the effective CEC of a mineral soil is less than 80% saturated with nonacid cations (i.e., more than 20% acid saturated), aluminum toxicity is likely to be a problem. Figure 9.7 illustrates that soil pH is more closely related to the acid cation saturation *percentage* than to the *absolute amount* of exchangeable acid cations in a soil.

While the factors responsible for soil acidity are far from simple, the described relationships indicate that two dominant groups of elements are in control. Aluminum-containing ions and H^+ ions generate acidity, while most of the other cations do not. This simple statement is worth remembering.

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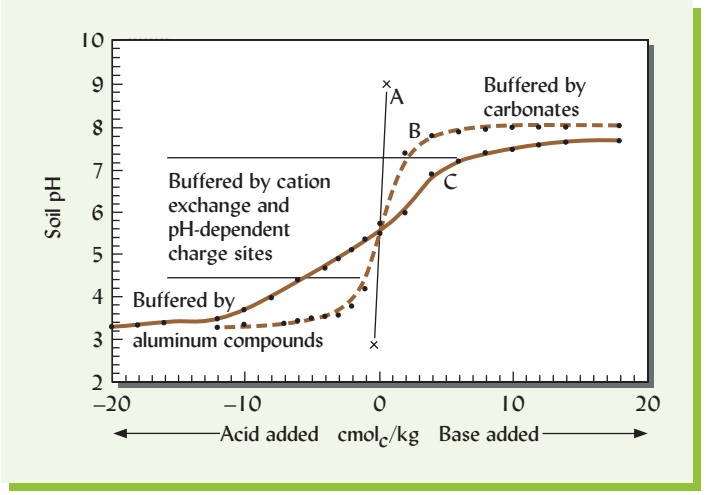

Figure 9.8 *Buffering of soils against changes in pH when acid (H_2SO_4) or base ($CaCO_3$) is added. A well-buffered soil (C) and a moderately buffered soil (B) are compared to unbuffered water (A). Most soils are strongly buffered at low pH by the hydrolysis and precipitation of aluminum compounds and at high pH by the precipitation and dissolution of calcium carbonate. Most of the buffering at intermediate pH levels (pH 4.5–7.5) is provided by cation exchange and protonation or deprotonation (gain or loss of H^+ ions) of pH-dependent exchange sites on clay and humus colloids. The well-buffered soil (C) would likely have a higher amount of organic matter and/or more highly charged clay than the moderately buffered soil (B).* [Curves based on data from Magdoff and Bartlett (1985) and Lumbanraja and Evangelou (1991)]

9.4 BUFFERING OF pH IN SOILS[4]

Soils tend to resist change in the pH of the soil solution when either acid or base is added. This resistance to change is called **buffering** and can be demonstrated by comparing the *titration curves* for pure water with those for various soils (Figure 9.8).

Titration Curves

A titration curve is obtained by monitoring the pH of a solution as an acid or base is added in small increments. For example, consider the addition of 0.1 cmol$_c$ of a strong acid like HCl to a liter of water initially at pH 6 (in which the H^+ ion concentration $= 10^{-6} = 0.000001$ mol/L). The acid supplies 0.001 mol (= 0.1 cmol) of H^+ ions. Because the water is unbuffered, the new H^+ concentration is 0.001001, which is approximately 10^{-3} mol/L or pH 3. The pH has dropped about three units (from pH 6 to about pH 3) in response to this tiny addition of acid (Curve A in Figure 9.8). If the same amount of acid were added to soil, the change in pH would be almost too small to measure (Curves B and C in Figure 9.8). By comparing the slopes of these titration curves, we can conclude that the better buffered the soil, the smaller the change in pH caused by a given addition of acid (or base).

The titration curves shown in Figure 9.8 suggest that the soils are most highly buffered when aluminum compounds (at low pH) and carbonates (at high pH) are controlling the buffer reactions. The soil is least well buffered at intermediate pH levels where H^+ ion dissociation and cation exchange are the primary buffer mechanisms. Different soils exhibit different titration curves reflecting differences among soils with regard to the amounts and types of dominant colloids, carbonates, and bound Al–hydroxy complexes.

Mechanisms of Buffering

For soils with intermediate pH levels (5–7), buffering can be explained in terms of the equilibrium that exists among the three principal pools of soil acidity: active, salt-replaceable, and residual (Figure 9.9). If just enough base (lime, for example) is applied to neutralize the H^+ ions in the soil solution, they are largely replenished as the reactions move to the right, thereby minimizing the change in soil solution pH (Figure 9.9). Likewise, if the H^+ ion concentration of the soil solution is increased (e.g., by organic decay or fertilizer applications) the reactions in Figure 9.9 are forced to the left, consuming most of the added H^+ and again minimizing changes in soil solution pH. Because of the involvement of residual and exchangeable acidity, we can see that soils with higher clay and organic matter contents are likely to be better buffered in this pH range.

[4]For a detailed discussion of the chemical principles behind this and related topics, see Bloom et al. (2005).

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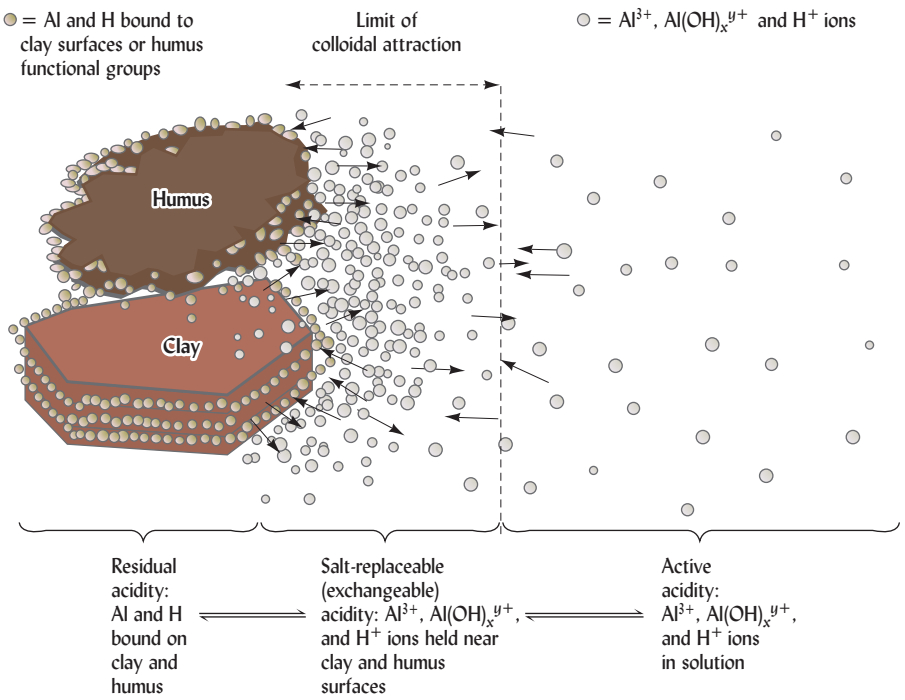

Figure 9.9 *Equilibrium relationships among residual, salt-replaceable (exchangeable), and soil solution (active) acidity in a soil with organic and mineral colloids. Adsorbed (exchangeable) and residual (bound) ions are much more numerous than those in the soil. Bound aluminum is held tightly on the surfaces of the clay or humus. Remember that aluminum ions, by hydrolysis, also supply H^+ ions in the soil solution. Neutralizing only the hydrogen and aluminum ions in the soil solution will be of little consequence as they will be quickly replaced by ions associated with the colloid. The soil, therefore, demonstrates high buffering capacity.* (Diagram courtesy of Ray R. Weil)

Throughout the entire pH range, reactions that either consume or produce H^+ ions provide mechanisms to buffer the soil solution and prevent rapid changes in soil pH. Five principal mechanisms are:

1. Hydrolysis, dissolution, or precipitation of gibbsite [$Al(OH)_3$] and other aluminum and iron hydroxyoxide clay minerals (Section 9.2);
2. Protonation or deprotonation of organic matter functional (R–OH) groups (Figure 8.16);
3. Protonation or deprotonation of pH-dependent charge sites on clay minerals (Figure 8.19);
4. Cation exchange reactions (Section 8.8);
5. The dissolution or precipitation of carbonate minerals (Section 9.8).

Why is Soil pH Buffering Important?

Soil buffering is important for two primary reasons. First, buffering tends to ensure some stability in the soil pH, preventing drastic fluctuations that might be detrimental to plants, soil microorganisms, and aquatic ecosystems. For example, well-buffered soils resist the acidifying effect of acid rain, preventing the acidification of both the soil and the drainage water. Second, buffering influences the amount of amendments, such as lime or sulfur, required to bring about a desired change in soil pH.

Soils vary greatly in their buffering capacity. Other things being equal, the higher the CEC of a soil, the greater its buffering capacity. This relationship exists because in a soil with a high CEC, more reserve and exchangeable acidity must be neutralized or increased to affect a given change in soil pH. Thus, a clay loam soil containing 6% organic matter and 20% of a 2:1-type clay would be more highly buffered than a sandy loam with 2% organic matter and 10% kaolinite (Figure 9.10).

9.5 HOW CAN WE MEASURE SOIL pH?

More may be inferred regarding the chemical and biological conditions in a soil from the pH value than from any other single measurement. Soil pH can be easily and rapidly measured in the field by colorimetric or potentiometric methods (Figure 9.11).

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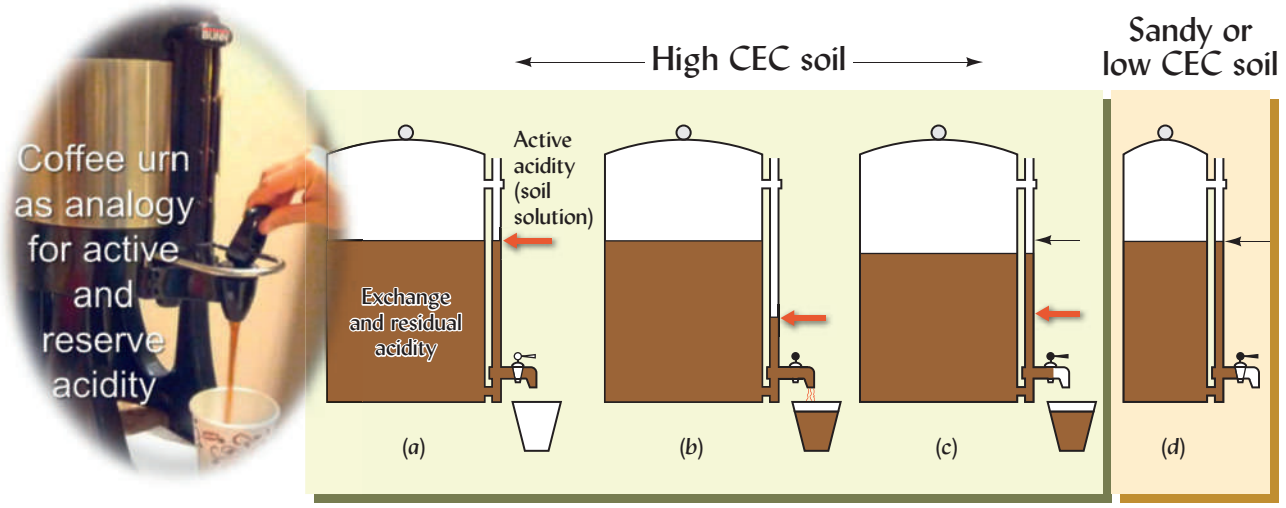

Figure 9.10 *The buffering capacity of soils can be described by using the analogy of a coffee dispensing urn. (a) The active acidity, which is represented by the coffee in the indicator tube on the outside of the urn, is small in quantity. (b) When H^+ ions are removed, this active acidity falls rapidly. (c) The active acidity is quickly restored to near the original level by movement from the exchange and residual acidity. By this process, the active acidity resists change. (d) A second soil with the same active acidity (pH) level but much less exchange and residual acidity would have a lower buffering capacity. Much less coffee would have to be added to raise the indicator level in the last dispenser. So too, much less liming material must be added to a soil with a small buffering capacity in order to achieve a given increase in the soil pH.*

Figure 9.11 *Soil pH may be determined in the field using either (a) chemical dyes or (b) miniaturized pH meters. The color of the chemical dye changes in response to pH and can be compared to a standard color chart to estimate pH to within 0.2–0.5 units. The pH of the soil at left was 6.5, matching the color of the fourth chip from the top. The battery powered miniature pH meters use the same type of H^+ ion sensing electrode as the laboratory models and can indicate pH to within 0.01 units. Other types of meters on the market (c) claim to measure soil pH using one to three metal rods that are inserted into the soil, but these types of meters are without scientific foundation and can give highly misleading readings (the meter shown at right is reading pH 8 but the actual pH of that soil was 5.2).* (Photos courtesy of Ray R. Weil)

Potentiometric Methods

The most accurate method of determining soil pH is with a pH-sensitive *glass* electrode and a standard reference electrode (or a probe that combines both electrodes in one, Figure 9.12). The pH electrode is inserted into a soil:water suspension (usually at a ratio of 1:1 or 1:2.5). The difference between the H^+ ion activities in the soil suspension and in the glass electrode gives rise to an electrometric potential that is related to the soil solution pH. A special meter (called

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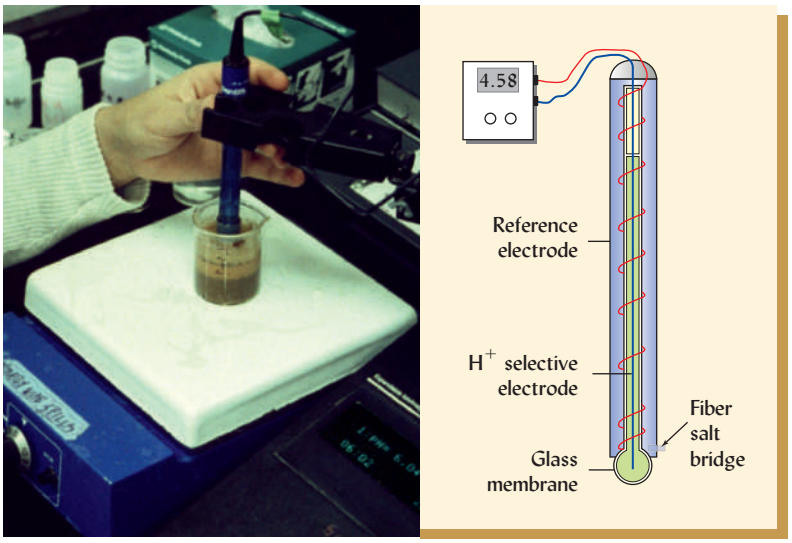

Figure 9.12 *Soil pH is measured accurately and inexpensively in the laboratory using a pH meter (a sensitive millivolt meter that converts readings to pH) connected to a combination pH electrode that consists of a reference electrode constructed around a H^+-sensing glass membrane electrode (diagram). A mixture of soil and water (in beaker) is stirred and the electrode is immersed in the suspension. The H^+ ions create an electrical potential once the salt bridge completes the circuit. One technician can make hundreds of determinations in a day.*
(Photo and diagram courtesy of Ray R. Weil)

a *pH meter*) is used to measure the electrometric potential in millivolts and convert them into pH readings. The glass electrode is what makes this system sensitive to H^+ ion activities. Be advised that certain metallic soil probes on the market that do *not* contain a glass electrode cannot measure pH as claimed and may give highly misleading readings (Figure 9.11*c*).

Most soil-testing laboratories (see Section 16.11) in North America measure the pH of a suspension of soil in water. This is designated the pH_{water}. Other labs may report lower soil pH readings because they suspend the soil in a salt solution instead of in pure water (see Box 9.2). In this textbook, we will report values for pH_{water}, unless specified otherwise.

Variability in the Field

Spatial Variation. Soil pH may vary dramatically over very small distances (millimeter or smaller). For example, plant roots may raise or lower the pH in their immediate vicinity, making the soil pH around the roots quite different from that in the bulk soil just a few mm away (Figure 9.14). Thus, the root may experience a very different chemical environment from that indicated by lab measurements of bulk soil samples. Such mm-scale variability may account in part for the great diversity in microbial species present in normal soils (see Chapter 11).

Concentrations of fertilizers or ashes from forest fires may cause sizeable pH variations within the space of a few centimeters to a few meters. Other factors, such as erosion or topography-related drainage, may cause pH to vary considerably over larger distances (hundreds of m), often ranging over two or more pH units within a few hectares. A carefully planned sampling procedure may minimize errors due to such variability (see Section 16.11). In addition to differences from place to place, a sampling scheme should also recognize variations with depth and time.

With Soil Depth. Different horizons, or even parts of horizons, within the same soil may exhibit substantial differences in pH. In many instances, the pH in the upper horizons is lower than in the deeper horizons (see Figure 9.6), but many patterns of variability exist. Acidifying processes usually proceed initially near the soil surface and slowly work their way down the profile. Examples include the acid input from rainfall, the oxidation of nitrogen applied as fertilizer to the soil surface, and the decomposition of plant litter falling on the soil surface. Reinforcing this vertical pH trend, many natural alkalizing processes such as mineral weathering are typically most active in the lower soil horizons where weatherable minerals from the parent material are most plentiful.

Human application of liming materials is one of the more obvious exceptions to the already described trends since this practice raises the pH mainly in the upper horizons into which the lime is incorporated. The incorporation of liming materials into the Ap horizon by tillage usually results in relatively uniform pH readings within the top 15–20 cm of cultivated soil.

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BOX 9.2

TAKE YOUR SOIL pH WITH A PINCH OF SALT

In North America, most labs use **pure water** to make the soil suspension used in measuring pH, giving results reported as pH_{water}. Two important drawbacks to this method are that it is sensitive to: (1) the soil:water ratio used and (2) small variations in the soluble salt content of soil. For example, fertilizer additions or evaporative salt accumulation can cause pH_{water} readings to differ by as much as 0.5 units even though soil acidity remains constant.

These problems can usually be overcome by a second method using a weak, unbuffered salt solution instead of pure water to make the soil suspension. Most commonly, a **0.01 *M* $CaCl_2$ solution** is used to provide a background electrolyte concentration sufficient to minimize variations caused by most salt accumulations or chemical fertilizer applications. The Ca^{2+} ions added in the solution force a portion of the exchange acidity to move into the active pool, giving pH_{CaCl} readings that are typically 0.2–0.5 units lower than pH_{water} readings for the same soil. Many soil test labs in Europe and Australia routinely report pH_{CaCl_2} rather than pH_{water}.

A third method in common use involves mixing the soil with a **solution of 1 *M* KCl**. Enough K^+ ions are supplied to completely exchange with cations on the soil's CEC, thus forcing the exchangeable pool of acidity into the soil solution where the pH is measured. The pH_{KCl} is unaffected by salinity variations in the soil and may give an indication of the active plus exchangeable (salt-replaceable) pools of acidity. Figure 9.13 shows that values of pH_{KCl} average about 1 unit lower than for pH_{water}. The data points in Figure 9.13 are scattered rather widely because for any individual soil, the effect of KCl depends on such soil properties as ion exchange capacity, type of colloids, and initial soluble salt content. In certain highly weathered, acid soils, pH_{KCl} may actually be *higher* than pH_{water}. Such would be the case if *anion* exchange capacity exceeds *cation* exchange capacity so that the dominant effect of using KCl would be that Cl^- ions force more OH^- ions from anion exchange sites into the bulk solution.

If subsamples of a soil were sent to three labs, the labs might report that the soil pH was 6.5, 6.0, or 5.5 (if the labs used methods for pH_{water}, pH_{CaCl_2}, and pH_{KCl}, respectively). All three pH values indicate the same level of acidity—and a suitable pH for most crops. Therefore, to interpret soil pH readings or compare reports from different laboratories, it is essential to know the method used.

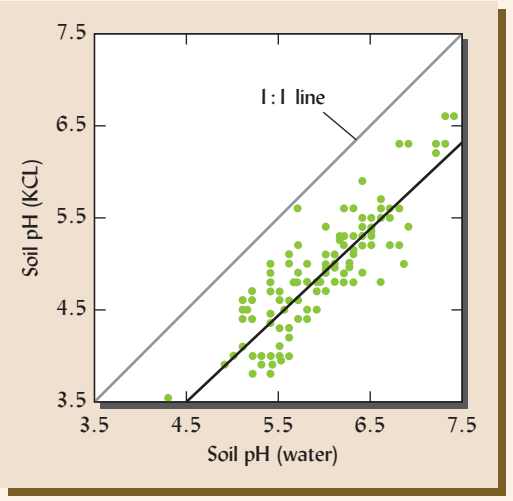

Figure 9.13 *Relationship between soil pH_{KCl} and pH_{water} for 151 diverse surface soils.* [Data from Weil (2000), Lumbanraja and Evangelou (1991), Falkengren-Grerup et al. (2006), and Stine and Weil (2002)]

However, severe acidity may occur in the subsoil beyond the depth of lime incorporation but within the reach of most plant roots. Untilled soils—including croplands managed with no-till practices, unplowed grasslands, lawns, and forest land—often show marked vertical variation in soil pH, with most of the changes in pH occurring in the upper few cm (see Figure 9.15).

For all these reasons, it is often advisable to obtain soil samples from various depth increments within the root zone and determine the pH level for each. Otherwise, serious acidity problems may be overlooked.

Effects of Season and Time. A buildup of salts near the surface during dry periods versus the leaching of these salts during wet periods often produce seasonal variations in soil pH_{water}. Other causes of seasonal variation include periods of intense organic decay with the onset of warm temperatures or first rains. Because of such variations, successive soil samples should be collected at the same time of year if changes in pH are to be monitored over a number of years.

Most acidification processes are quite slow and must overcome soil buffering, so field soil pH generally changes slowly over a period of years or decades (see Figure 9.15). However, if finely ground, reactive amendments (lime or sulfur) are applied, changes of 1 or more pH units may occur within a few months (see Section 9.8).

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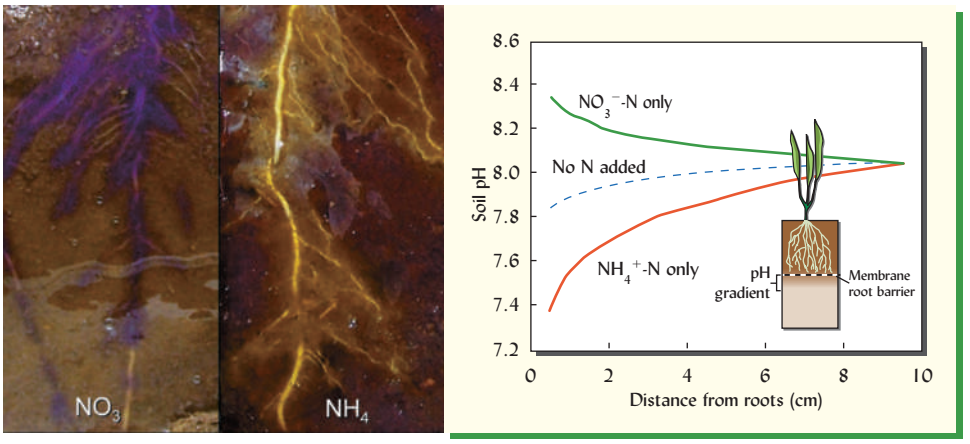
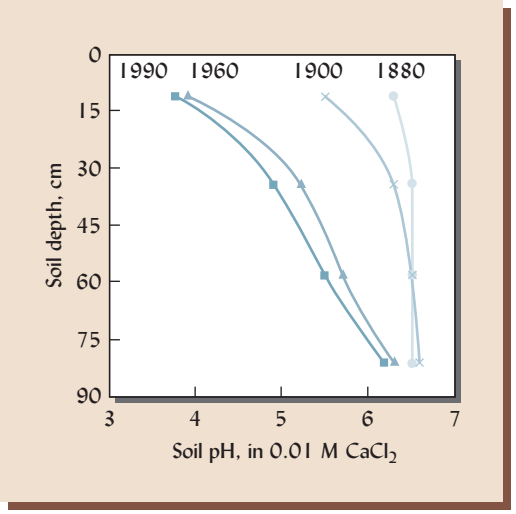


Figure 9.14 *Soil pH at near plant roots receiving either ammonium (NH_4^+) or nitrate (NO_3^-) or no nitrogen fertilizer. Uptake of NH_4^+ cations causes the roots to release equivalent positive charges in the form of H^+ cations, which lower the pH (see Reaction (9.7) causing the pH-sensitive dye to turn yellow* (middle)*. When a NO_3^- anion is taken up, the roots release a bicarbonate anion (HCO_3^-), which raises the pH (see Reaction (9.8) causing a purple color in a pH dye impregnated soil* (far left)*. The soil used in another experiment illustrated at right was a calcareous sandy clay loam in the Aridisols order with pH = 8.1. In this experiment, soil pH was measured using a tiny pH sensor. The roots using NH_4^+ lowered the pH of the soil and the more acid conditions markedly enhanced the plant's uptake of phosphorus by increasing the solubility of calcium phosphate minerals near the root. In more acid soils, the reduced pH might increase the toxicity of aluminum. A barrier membrane allowed soil solution to pass through, but prevented root growth into the lower soil where pH was measured. Plants were watered from the bottom by capillary rise.* [Diagram drawn from data in Zhang et al. (2004) with permission of the Soil Science Society of America. Left photos courtesy of Joseph Heckman, The Rutgers University]

Figure 9.15 *The change in soil pH (measured in 0.01 M $CaCl_2$) during a 110-year period in which a former agricultural field was allowed to revert to natural vegetation (eventually a mature oak forest). The fine-textured (clay loam to clay) Alfisol at Rothamstead in England was untilled, unfertilized, and unlimed. Note that in the first 20 years acidification was most pronounced near the soil surface. In the ensuing years acidity continued to increase most dramatically at the surface, but eventually increased throughout the profile. By 1960, the surface horizon had reached the pH range in which strong buffering by aluminum compounds probably slowed acidification.* [Drawn from data in Blake et al. (1999); used with permission of Blackwell Science, Ltd]



9.6 HUMAN-INFLUENCED SOIL ACIDIFICATION[5]

In certain situations, the natural processes of soil acidification are greatly (and usually inadvertently) accelerated by human activities. We will consider three major types of human-influenced soil acidification: (1) nitrogen amendments, (2) acid precipitation, and (3) acid sulfate soils.

Nitrogen Fertilization

During the past 100 years, agricultural activities have greatly increased the amount of nitrogen cycling through the world's soils (Section 13.9). This intensification of nitrogen cycling,

[5]Rice and Herman (2012) reviewed human-influenced acidification of Earth's air, waters, and soils. Ritchey et al. (2015) provide a clear example of acidification by a legume cover crop.

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largely by the use of chemical fertilizers, has helped global food supplies stay ahead of population growth (Section 20.10), but has also accelerated acidification of the world's cropland soils.

Chemical Fertilizers. Widely used ammonium-based fertilizers, such as ammonium sulfate [$(NH_4)_2SO_4$] and urea [$CO(NH_2)_2$] are oxidized in the soil by microbes to produce strong inorganic acids by reactions such as the following:

$$(NH_4)_2SO_4 + 4O_2 \rightleftharpoons \underset{\text{Nitric acid}}{2HNO_3} + \underset{\text{Sulfuric acid}}{H_2SO_4} + 2H_2O \qquad (9.17)$$

These strong acids provide H^+ ions that lower pH, as shown in Figure 9.17 by the relationship between the rate of N fertilizer applied and the drop in pH of a cropped Mollisol in north central USA. However, since H^+ ions are consumed by the bicarbonate released when plants take up nitrate anions (Reaction [9.8]), net soil acidification results largely from that portion of applied nitrogen that is not actually used. Thus soil acidification is often tied to the excessive use of nitrogen fertilizer, as popularized in many countries during the second half of the twentieth century (Sections 13.15 and 16.13). As farmers in China use N fertilizers at increasingly heavy rates, cropland soils there also are acidifying. The acidification of cropland soils results mainly from ammonium oxidation and subsequent nitrate leaching, but also is stimulated by increased crop yields and their associated heavy uptake and removal of nonacid cations (Ca, Mg, and K) (Figure 9.16). The use of nitrogen-fixing legumes in crop rotations and as cover crops can also acidify soils via the production of ammonium nitrogen and a similar imbalance between anion and cation uptake.

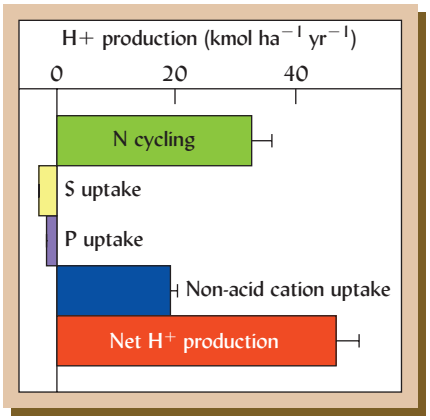

Figure 9.16 *Net H^+ ion production indicates acidification of wheat-maize cropland in China. The main drivers of acidification were nitrogen cycling (mainly ammonium oxidation and leaching of nitrate) and crop uptake and harvest of nonacid cations (mainly Ca, Mg, and K). These acidifying processes were only slightly counterbalanced by H^+ ion consumption with the crop uptake of S and P as anions.* [Drawn from data in Guo (2010)]

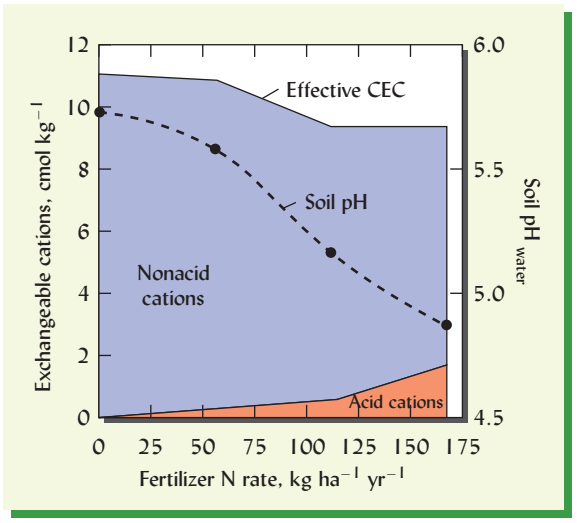

Figure 9.17 *Fertilization with ammonium forms of nitrogen can significantly lower soil pH. Excess H^+ ions are generated during the bacterial conversion of NH_4^+ to NO_3^-. The acidification is especially severe if more NO_3^- is created than plants can take up and if most of the nonacid cations taken up by the plants are removed by harvest. As a result of the declining pH, the effective cation exchange capacity (CEC) of the soil also declines (see also Section 8.9). In the case illustrated, a Mollisol in Wisconsin, USA, was fertilized with N (urea or ammonium nitrate) for 30 years at the rates indicated. Conventional plow tillage was used to grow corn, soybean, and tobacco crops, and all the aboveground residues were removed.* [Redrawn from data in Barak et al. (1997)]

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Acid-Forming Organic Materials. Application of organic materials such as animal manures, composts, sewage sludge, and some types of plant litter can decrease soil pH, both by oxidation of the ammonium nitrogen released and by organic and inorganic acids formed during decomposition. Some types of compost or plant material contain enough nonacid cations to partially or completely replace those lost by acid leaching, and therefore these organic materials may have little or no net acidifying effect when applied to soils. The composition of regularly applied organic amendments must be known to determine if a program of regular additions of liming materials will be needed to counteract acidification. In many countries, after the application of sewage sludge, regulations require that soil pH be maintained near neutral to minimize the mobility of toxic metals found in this type of waste material (see Section 18.8). In order to control pathogens and odors, certain types of sewage sludge are mixed with large amounts of lime. Rather than acidifying the soil, application of such lime-stabilized sewage sludge may result in **overliming** if the lime content is not taken into account when determining application rates.

Acid Deposition from the Atmosphere

Origins of Acid Rain. Combustion of fossil fuels and the smelting of sulfur-containing metal ores emit enormous quantities of nitrogen and sulfur-containing gases into the atmosphere (Figure 9.18). Other sources of these gases include forest fires and the burning of crop residues. The gases (mainly sulfur dioxide and oxides of nitrogen) react with water and other substances in the atmosphere to form HNO_3 and H_2SO_4. These strong acids are then returned to the Earth in *acid rain*, a popular term which we will use here to include all forms of acidified precipitation: rain, snow, fog, and dry deposition. Normal rainwater that is in equilibrium with atmospheric carbon dioxide has a pH of about 5.5. The pH of acid rain commonly is between 4.0 and 4.5, but may be as low as 2.0. The greatest amount of acidity currently falls on regions downwind from major industrial centers, including much of Europe, central Russia, eastern China, and the eastern part of North America.

Effects of Acid Rain. Acid rain causes expensive damage to buildings and car finishes, but the principal environmental reasons for concern about acid rain are its effects on (1) fish and

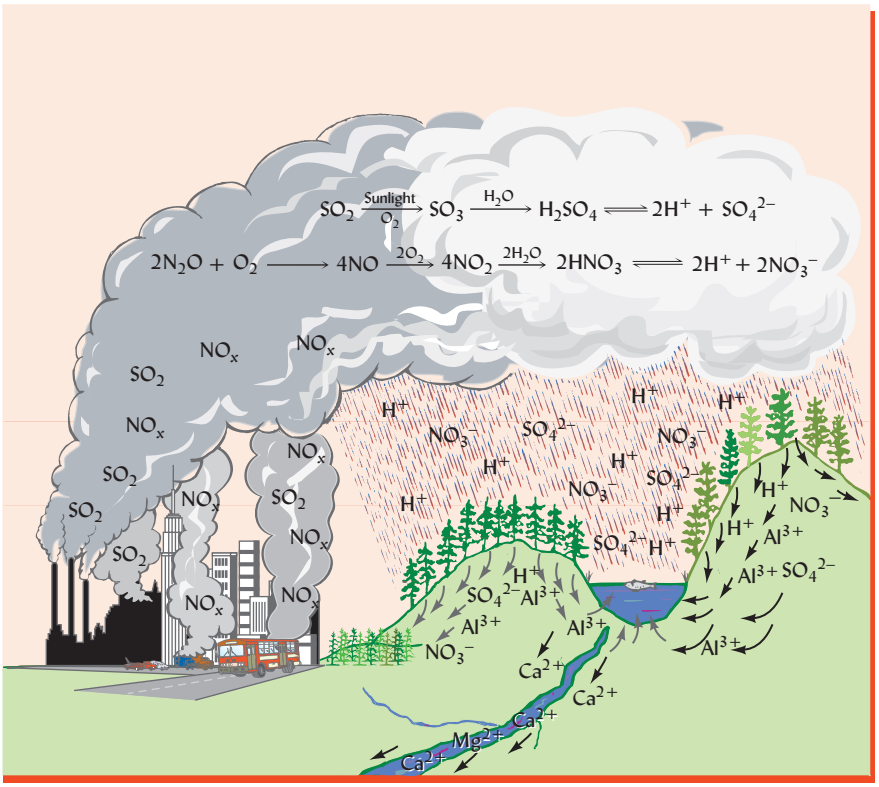

Figure 9.18 *Simplified diagram showing the formation of acid rain in urban areas and its impact on distant watersheds. Combustion of fossil fuels in electric power plants and in vehicles accounts for the largest portions of the nitrogen and sulfur emissions. About 60% of the acidity is due to sulfur gases and about 40% is due to nitrogen gases. The gases are carried hundreds of kilometers by the wind and are oxidized to form sulfuric and nitric acid in the clouds. These acids then return to Earth in precipitation and in dry deposition. The H^+ cations and NO_3^- and SO_4^{2-} anions cause acidification to occur in soils, soil aluminum to mobilize, and the loss of calcium and magnesium to accelerate. The mobilized aluminum percolates through the soil mantle, eventually reaching lakes and streams. The principal ecological effects of concern in sensitive watersheds are: (1) possible decline in forest health and (2) decline or even death of aquatic ecosystems.* (Diagram courtesy of Ray R. Weil)

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(2) forests. Since the 1970s, scientists have documented the loss of normal fish populations in thousands of lakes and streams. More recently, studies have suggested that the health of certain forest ecosystems is suffering because of acid rain. Furthermore, scientists have learned that the health of both the lakes and the forests is not usually affected directly by the rain, but rather by the interaction of the acid rain with the soils in the watershed (Figure 9.18).

Soil Acidification. The incoming strong acids mobilize aluminum in the soil minerals, and the Al^{3+} displaces Ca^{2+} and other nonacid cations from the exchange complex. The presence of the strong acid anions (SO_4^{2-} and NO_3^-) facilitates the leaching of the displaced Ca^{2+} ions (as explained in Figure 9.3). Soon Al^{3+} and H^+ ions, rather than Ca^{2+} ions, become dominant on the exchange complex, as well as in the soil solution and drainage waters. Figure 9.19 illustrates the acidification of a reforested soil over a 50-year period. However, in this and other studies, it is not easy to sort out how much acidification is due to natural processes internal to the soil ecosystem (see left side of Table 9.1) and how much is due to acid rain. Different studies estimate that acid deposition has caused 30–80% of the observed acidification in humid regions receiving highly acid rain.

Effects on Forests. Some scientists are concerned that trees, which have a high requirement for calcium to synthesize wood, may eventually suffer from insufficient supplies of this and other nutrient cations in acidified soils. Research has shown reductions in Ca^{2+}, Mg^{2+}, and K^+ and declines in pH levels over several decades in forested watersheds subject to acid rain deposits. The leaching of calcium and the mobilization of aluminum may result in Ca/Al ratios (mol_c/mol_c) of less than 1.0 in both the soil solution and on the exchange complex. A Ca/Al ratio of 1.0 is widely considered a threshold for aluminum toxicity, reduced calcium uptake, and reduced survival for forest vegetation. While there is little doubt that aluminum in acidified soils is toxic to many forest species (see Section 9.7), the scientific evidence for forest calcium deficiencies is less clear. The calcium supply in most forested soils in humid temperate regions is being depleted as the rate of calcium loss by leaching, tree uptake, and harvest exceeds the rate of calcium deposition. In some cases forest ecosystems have responded to applications of calcium compounds (carbonates or silicates) by increased tree nitrogen capture and utilization and improved stream water quality. However, it seems that even in very acid soils low in exchangeable Ca^{2+}, the weathering of soil minerals often releases sufficient calcium for good tree growth—at least in the short term.

Effects on Aquatic Ecosystems. The water draining from acidified soils often contains elevated levels of aluminum, as well as sulfate and nitrate. When this aluminum-charged soil drainage eventually reaches streams and lakes, these bodies of water become lower in calcium, less well-buffered, more acid, and higher in aluminum. The aluminum is directly toxic to fish, partly because it damages gill tissues. As the lake

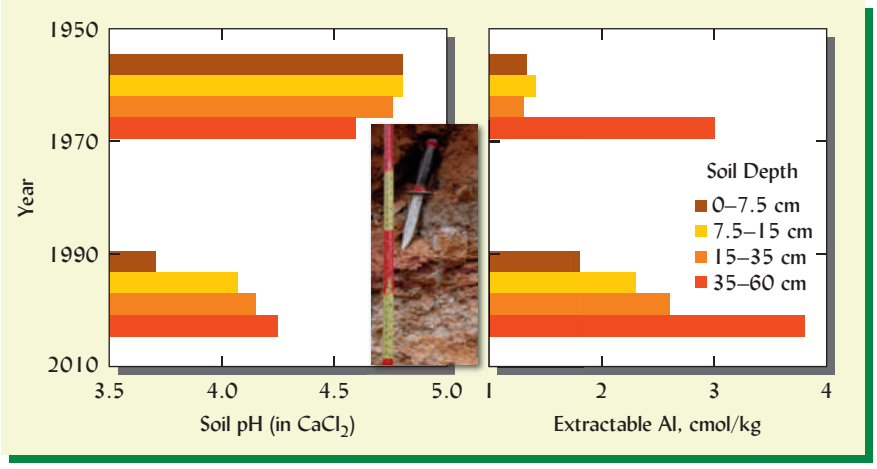

Figure 9.19 *Changes in soil acidity in a South Carolina Ultisol profile during a half century under a loblolly pine forest. The soils at this site were limed regularly for agricultural crops before undergoing reforestation in 1952 and therefore were less acid at the beginning of the study than they would have been in their natural state. The effective CEC for these soil horizons ranged from 0.8 to 3.3 $cmol_c$/kg (data not shown). Note that the greatest acidification took place in the uppermost mineral horizon (0–7.5 cm), but the greatest concentration of oxalate extractable Al (shown for the year 2000) occurred in the deeper horizons that contained the least organic matter (see also Section 9.7). The rapid acidification was driven mainly by tree uptake of nonacid cations and by inputs of acidic pine organic litter and deposition of acidic precipitation.* [Drawn from data cited in Richter (2007)]

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BOX 9.3

HOW MUCH ACIDITY FALLS IN ACID RAIN?

To use an example typical of the area most impacted by acid rain in North America, consider 1 m^2 of land in a humid region with 1000 mm of annual rainfall at pH 4 (i.e., H^+ concentration of 0.0001 mol/L). This area of land would annually receive 1000 L of rain (1 m^3 of water) carrying 0.0001 mol of H^+ ion/L for a total of $1000 \times 0.0001 = 0.1$ mol of H^+ ions per m^2 of land. Assume that this rain reacts mainly with the top 20 cm of soil (0.2 m^3), consisting of 10 cm of organic O_i, O_e horizons underlain by 10 cm of sandy E horizon. In that 1 m^2, the O horizons might weigh about 50 kg, assuming a bulk density = 0.5 Mg/m^3, and the E horizon might weigh about 140 kg assuming a bulk density = 1.4 Mg/m^3. The soil, a Spodosol typical of many areas sensitive to acid rain, would be already quite acid, say, pH = 4.0. It might have an effective CEC in the O horizons of about 50 $cmol_c$/kg and in the E horizon of about 4 $cmol_c$/kg. Therefore, in this case, the acidity in the annual rainfall (10 cmol H^+/m^2) would be the equivalent of about 0.4% of the O horizons' CEC or about 1.8% of the E horizon's CEC:

Acid input as percentage of O horizon CEC

Acid input: 0.1 mol H^+/50 kg soil
$= 2 \times 10^{-3}$ mol H^+/kg = 2 mmol H^+/kg = 0.2 $cmol_c$ H^+/kg

Percentage of CEC:
(0.2 $cmol_c$ H^+/kg)/(50 $cmol_c$ CEC/kg) × 100 = 0.4%

Acid input as percentage of E horizon CEC

Acid input:
0.1 mol H^+/140 kg soil $= 7 \times 10^{-4}$ mol H^+/kg
= 0.7 mmol H^+/kg
= 0.07 $cmol_c$ H^+/kg

Percentage of CEC:
(0.07 $cmol_c$ H^+/kg)/(4 $cmol_c$ CEC/kg) × 100 = 1.8%

The degree to which the incoming H^+ ions actually would replace exchangeable nonacid cations would depend on the conditions of cation exchange (see Section 8.8) and on such factors as how much of this acidity could be consumed by weathering Ca and other cations from the soil minerals, etc. Remember that acidification will occur only to the degree that H^+ ion generation exceeds H^+ ion consumption (by the processes listed in Table 9.1).

In our example, a H^+ ion input of the magnitude just considered would cause only a very small change in residual acidity and almost no measurable change in pH from year to year. However, in a more poorly buffered soil (e.g., if some disturbance had caused our Spodosol to lose its O horizons), residual acidity would increase and the pH of the soil solution and drainage water would soon decline significantly.

water pH drops to about 6.0, acid-sensitive organisms in the aquatic food web die off, and reproductive performance of such fish as trout and salmon declines. With a further drop in water pH to about 5.0, virtually all fish are killed. Although the acidified water may look crystal clear (in part due to the flocculating influence of aluminum), the lake or stream is considered to be "dead" except for a few algae, mosses, and other acid-tolerant organisms.

The quantity of HNO_3 and H_2SO_4 deposited globally in acid rain is enormous, but the amount falling on a given hectare in a year is usually not enough to significantly change soil pH in the short term (see Box 9.3). In time, however, the cumulative acid deposition negatively impacts soils, the plants growing in them, and the aquatic ecosystems receiving their drainage waters.

Sensitive Soils. Ecological damage from acid rain is most likely to occur where the rain is most acid and the soils are most susceptible to acidification. World soils have been grouped into five classes of acidification susceptibility based mainly on the soils' CEC and acid saturation percentage. Inclusion of other factors such as content of weatherable minerals would make this classification more precise, but the general trends are clear. Ecosystems in eastern China and Brazil are among those most likely to be damaged in the future if effective steps to control acid rain are not undertaken.

Slow Progress.[6] Since the passage of the U.S. Clean Air Act in 1970, the atmospheric deposition of sulfates in North America has declined significantly. Unfortunately, the alkalinity of

[6]The recovery of forests, lakes, and streams from acidification in North America and Europe has been intensively studied (Lawrence et al., 2011) and (Löfgren et al., 2009). Evidence is also mounting of the importance of soil calcium in forest acidification and nitrogen utilization (Bal et al. 2015), (Cho et al., 2012) and (Greaver et al., 2012).

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many streams and lakes in the Northeast has not increased as rapidly as would be expected to accompany the decline in sulfates. One explanation for the delayed recovery is that air pollution controls did an even better job of removing particulate pollutants from smokestack emissions. These tiny soot particles happen to be rich in calcium, so their removal in the interest of clean air resulted in less calcium deposition on acidified watersheds. Another important source of Ca deposition—dust from traffic on unpaved roads—has also declined in recent decades. In addition, acidification depletes calcium from forest soils by leaching losses. Applying calcium materials to huge tracts of forested land would be difficult (even by helicopter) and, in the long term, not sustainable.

Tightening air quality standards for both NO_x and SO_2, in conjunction with possible calcium amendments, is expected to continue to reduce acid inputs into sensitive ecosystems, eventually restoring a suitable chemical balance in the soils of these areas (and therefore in the lakes as well).

Exposure of Potential Acid Sulfate Materials[7]

Potential Acidity from Reduced Sulfur. A large pool of potential soil acidity may occur in soils or sediments that contain reduced sulfur. If drainage, excavation, or other disturbance introduces oxygen into these normally anaerobic soils, oxidation of the sulfur may produce large amounts of acidity. The adjective **sulfidic** is used to describe such materials with enough reduced sulfur to markedly lower the pH within two months of becoming aerated. The term **potential acidity** refers to the acidity that could be produced by such reactions.

Drainage of Certain Coastal Wetlands. Due to the microbial reduction of sulfates originally in seawater, many coastal sediments contain significant quantities of pyrite (FeS_2), iron monosulfides (FeS), and elemental sulfur (S). Coastal wetland areas in Southeast Asia, coastal Australia, northern Europe, West Africa, and the southeastern United States commonly contain soils formed in such sediments. So long as waterlogged conditions prevail, the ***potential* acid sulfate soils** retain the sulfur and iron in their reduced forms. However, if these soils are drained for agriculture, forestry, or other development, air enters the soil pores and both the sulfur (S^0, S^-, or S^{2-}) and the iron (Fe^{2-}) are oxidized, changing the potential acid sulfate soils into ***active* acid sulfate soils**. Ultimately, such soils earn their name by producing prodigious quantities of sulfuric acid, resulting in soil pH values below 3.5 and in some cases as low as 2.0. The principal reactions involved are:

$$\underset{\text{Pyrite}}{Fe^{II}S^{-I}_2} + 3\tfrac{1}{2}O_2 + H_2O \rightleftharpoons \underset{\text{Ferrous sulfate}}{Fe^{II}S^{VI}O_4} + \underset{\text{Sulfuric acid}}{H_2S^{VI}O_4}$$

$$\underset{\text{Ferrous sulfate}}{Fe^{II}SO_4} + \tfrac{1}{4}O_2 + 1\tfrac{1}{2}H_2O \rightleftharpoons \underset{\text{Iron oxyhydroxides}}{Fe^{III}OOH} + \underset{\text{Sulfuric acid}}{H_2SO_4} \qquad (9.18)$$

$$\underset{\text{Elemental S}}{S^0} + 1\tfrac{1}{2}O_2 + H_2O \longrightarrow \underset{\text{Sulfuric acid}}{H_2SO_4} \qquad (9.19)$$

Note that both oxidation of the S in pyrite and oxidation and hydrolysis of the Fe^{II} in $FeSO_4$ produce acidity. The sulfur is oxidized from a −1 to a +6 valence state and the iron is oxidized from +2 to +3. Inspection of Reactions (9.18) and (9.19) will reveal that two moles of acidity (one mole of H_2SO_4) are ultimately produced for each mole of S that reacts, whether

[7] Many of these sulfide-rich soils are clayey in texture and termed *cat clays* after the Dutch term *Kattecleigronden* which was given to land reclaimed from the ocean where acid sulfate clays with crusts of yellow jarosite somewhat resembled feline excrement. Baldwin (2011) and Ljung et al. (2009) describe some of the properties of these soils and discuss environmental problems that arise from their misuse. For a report on the iron and sulfur oxidizing roles of acidophile microorganisms, discovered growing at pH 0.5 in acid mine drainage, see Edwards et al. (2000).

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from FeS or elemental S. The oxidation reactions can occur by purely chemical means, but generally they are facilitated by microorganisms (such as the bacterium *Thiobacillus ferrooxidans* and the Archaeon *Ferroplasma acidipilum*) that make them proceed thousands of times faster, especially when warm, moist conditions favor microbial activity.

The iron sulfide compounds in the potential acid sulfate soils often give these soils a black color (Figure 4.2*d* and Figure 9.20*a*,*d*). The black color has sometimes led, with disastrous results, to the use of such soils by those seeking black, organic-matter-rich "topsoil" material for landscaping installations. The pH of the potential acid sulfate soils is in the neutral range (typically near 7.0) while they are still reduced, but drops precipitously within days or weeks of the soil being exposed to air. When in doubt, the pH of the soil should be monitored for several weeks while a sample is incubated in a moist, well-aerated, warm condition. See Figure 18.28 for an example of inappropriate, albeit inadvertent, engineering use of a potential acid sulfate clay.

Excavation of Pyrite-Containing Materials. Coastal marsh soils are not the only places where problems with acid sulfate soils occur. The sediments dredged to deepen shipping lanes in coastal harbors may also contain high concentrations of reduced sulfur compounds (Figure 9.20*a*). Furthermore, many sulfide-rich types of geological sediment long ago became sedimentary rock or parent materials for upland soils. Since coal seams usually occur between layers of sedimentary rock, it is not surprising that coal-mining operations often uncover large quantities of pyrite-containing shale and similar rocks. When these once deeply buried materials are exposed to air and water, the reduced sulfur and iron compounds in them begin to oxidize and hydrolyze by the types of reactions already shown. Again, the result is the production of sulfuric acid in large quantities (Figure 9.20*d*).

Figure 9.20 *Active acid sulfate soils can cause serious ecosystem disturbances when they release some of their potential acidity into the environment. (a) Sulfidic sediments dredged from the bottom of Baltimore harbor in the United States used as fill material on land are beginning to dry out and oxidize. The black sulfidic materials turn light brown as they oxidize and release orange-colored acidic drainage water. (b) Similar orange-colored acid is draining across a sidewalk in a new housing development where road grading exposed sulfidic layer of marine sediment in the substratum beneath these coastal plain soils. The area to the right where the drainage originates has failed to grow any vegetation as the soil pH was 3.4. (c) Orange-colored acid water draining from acid sulfate soils exposed by coal mining has killed all life in this mountain stream. (d) A close-up view of the active acid sulfate soil that was the source of the polluting drainage water. Again, the blue-black material is rich in iron sulfide which forms sulfuric acid as it oxidizes to the light brown color in the foreground.* (Photos courtesy of Ray R. Weil)

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As water percolates through such oxidizing materials, it becomes an extremely acid and toxic brew known as **acid mine drainage**. Typical acid mine drainage has a pH in the range of 0.5–2.0, but pH values *below zero*[8] have been measured! When this drainage water reaches a stream (as in Figure 9.20*c*), iron sulfates dissolved in the drainage water continue to produce acid by oxidation and hydrolysis. The aquatic community can be devastated by the pH shock and the iron and aluminum that are mobilized. Similar problems occur when road cuts or building excavations expose buried sulfide-containing layers (Figure 9.20*b*). An indication of the tremendous scale of this environmental problem is the fact that acid drainage from mining and other excavations is thought to account for nearly a quarter of the global sulfate input into the ocean. If sulfide-rich excavated material (often black or dark gray in color) is used to cover a site after mining has been completed, acid sulfate soils are likely to form, making revegetation of the site all but impossible. In many countries, environmental regulations are designed to prevent this from happening.

Avoidance as the Best Solution. The amount of sulfur present in such soil material is considered an indication of its **potential acidity**. If calcite is either naturally occurring in the soil or is added as a neutralizing agent, sulfuric acid from S oxidation may react with it to form gypsum:

$$\underset{\text{Sulphuric acid}}{H_2SO_4} + \underset{\text{Calcite}}{CaCO_3} + H_2O \longrightarrow \underset{\text{Gypsum}}{CaSO_4 \cdot 2H_2O} + \underset{\text{Carbon dioxide}}{CO_2} \qquad (9.20)$$

Equation (9.20) indicates that 1 mole of liming material ($CaCO_3$) would be required to eventually neutralize the sulfuric acid produced by the oxidation of 1 mole of reduced S. Since 1 mole of $CaCO_3$ equals 100 g and 1 mole of S equals 32 g, about 3 kg of limestone would be needed to neutralize the acidity from the oxidation of 1 kg of S. The enormous amounts of $CaCO_3$ required often make neutralization impractical in the field.

Usually the best approach to solving this environmental challenge is to *prevent* the S oxidation in the first place. This means that sulfide-bearing wetland soils are best left undisturbed or at least maintained under saturated, wetland-like conditions. In this manner, both damage to agricultural crops and the considerable expense of attempting to neutralize the acidity can be avoided. Preserving the wetland condition of the soils will also avoid contamination of water with acid drainage and will maintain the natural habitat for a diversity of wild plants and animals.

In the case of mining or other excavation, any sulfide-bearing materials exposed must be identified and eventually deeply reburied to prevent their oxidation. If some acid drainage is unavoidable (as from abandoned, poorly designed mines), an effective treatment is to route the acid water through a wetland, either natural or constructed for the purpose (see Section 7.7). The anaerobic wetland conditions will re-reduce the iron and sulfur, causing iron sulfide to precipitate, simultaneously raising the pH of the water and reducing the iron content.

9.7 BIOLOGICAL EFFECTS OF SOIL pH

The pH of the soil solution exerts a critical influence on the growth of all organisms that live in the soil, including plants, animals, and microbes. Although we have already mentioned some ways that soil acidity and alkalinity affect plant growth, we will now take a more detailed look at the impacts that various pH conditions have on soil organisms.

To nonadapted plants, strongly acid soil presents a host of problems. These include toxicities of aluminum, manganese, and hydrogen, as well as deficiencies of calcium, magnesium, molybdenum, and phosphorus. As it is difficult to separate one problem from another, the situation is sometimes simply referred to as the acid soil "headache."

[8]Surprised at the reference to pH value below zero? It is commonly taught that the pH scale ranges from 0 to 14. However, consider that a 1 *M* solution of HCl has a pH value = 1.0 (note that $10^0 = 1$) so a 10 *M* HCl solution would have a pH value = −1.0 ($10^{+1} = 10$ and the negative log of $10^{+1} = -1$).

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Aluminum Toxicity[9]

Aluminum toxicity stands out as the most common and severe problem associated with acid soils. Not only plants are affected; many bacteria, such as those that carry out transformations in the nitrogen cycle, are also adversely impacted by the high levels of Al^{3+} and $AlOH^{2+}$ that come into solution at low soil pH. As can be deduced from Figure 9.5, aluminum toxicity is rarely a problem when the soil pH is above about 5.2 (above pH_{CaCl} 4.8) because little aluminum exists in the solution or exchangeable pools above this pH level. Figure 9.21 (*left*) shows an exponential increase in solution Al^{3+} concentration typical of mineral soils as pH level drops from 5 to 4. Other toxic Al species, namely, $AlOH^{2+}$ and $Al(OH)_2^+$, also increase in solubility below pH 5, but their concentrations near pH 4 are 10–100 times smaller than that of Al^{3+} and are not shown in Figure 9.21. At comparable pH levels in most organic soil horizons (O horizons) and organic soils (Histosols), much less Al^{3+} comes into solution because there is far less total aluminum in these soils. Furthermore, in organic soils aluminum toxicity is much less of a problem and because aluminum ions are strongly attracted and bound to the carboxylic ($R–COO^-$) and phenolic ($R–CO^-$) sites on soil organic matter (review Figure 8.19), leaving much less of the toxic inorganic Al in solution. Studies have shown that aluminum can be effectively detoxified in acid soils by strong binding to high molecular weight organic compounds associated with stable soil organic matter or by weaker bonding with small organic molecules associated with microbial decomposition and root exudates.

Effects on Plants. When aluminum, which is not a plant nutrient, is taken into the root, most remains there and little is translocated to the shoot (except in aluminum accumulator plants such as tea, which may contain as much as 5000 ppm in the dry leaves). Therefore, analysis of leaf tissue is rarely a good diagnostic technique for aluminum toxicity. In the root, aluminum damages membrane sites where calcium is normally taken in and restricts cell wall

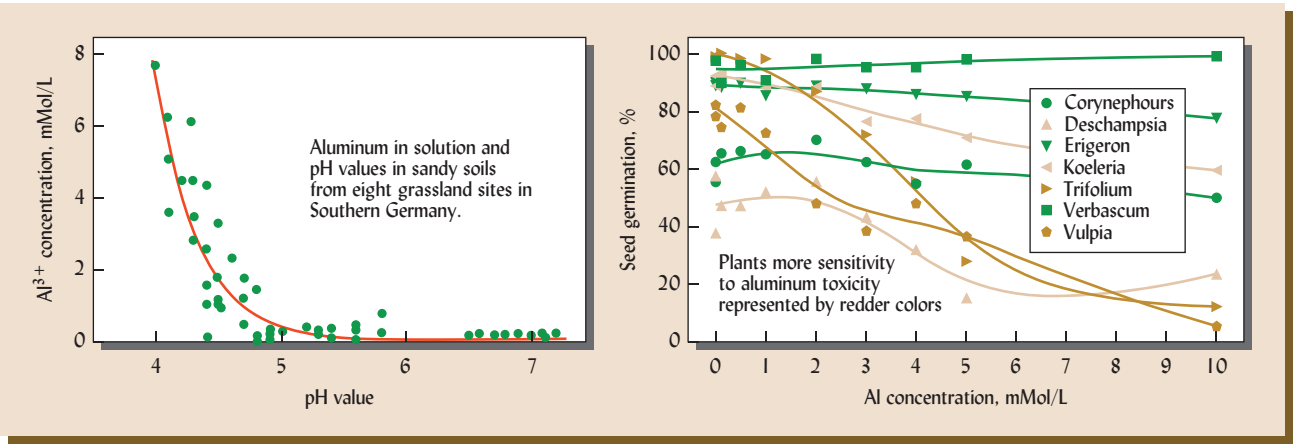

Figure 9.21 *Low soil pH levels bring toxic aluminum into solution and influence plant ecology. In a study of eight grassland sites with sandy soils in southern Germany, the soil pH level was closely related to the amount of Al^{3+} in the soil solution* (left). *As is typical for mineral soils, the Al^{3+} concentrations increase exponentially as pH values declined below 5.0, but little or no Al^{3+} occurs in solution when the pH level is greater than 5.5. The Al^{3+} in solution in mineral soils is thought to be largely controlled by the dissolution or precipitation of $Al[OH]_3^0$ coatings on particle surfaces. Depending on the plant's genetic adaptation, Al^{3+} concentration typical in mineral soils with H levels below 5.0 can cause dramatically stunted, dysfunctional root systems and other toxic effects, including inhibition of seed germination* (right). *A selection of native herbaceous plants from the grassland sites shows a high degree of variation in sensitivity of germination seeds to Al^{3+}, accounting for major differences in the plant species composition among the sites. Some species (green lines) were little affected by even high levels of Al^{3+} and therefore tended to dominate the most acid soils. Seed germination for the most aluminum-sensitive plants (red lines) declined dramatically when Al^{3+} concentrations exceeded 1 mM.* [Graphed from selected data in Abedi et al. (2013)]

[9]Several good reviews explain the soil chemistry of aluminum toxicity and the mechanisms of plant tolerance to aluminum (Hoekenga and Magalhaes, 2011; Ryan and Delhaize, 2012).

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expansion so roots cannot grow properly (Figure 9.22, *left*). Aluminum also interferes with the metabolism of phosphorus-containing compounds essential for energy transfers (ATP), genetic coding (DNA), and seed germination (Figure 9.21, *right*).

Symptoms. The most common symptom of aluminum toxicity is a stunted root system with short, thick, stubby roots that show little branching or growth of laterals (Figure 9.23). The root tips and lateral roots often turn brown. In some plants, the leaves may show chlorotic (yellowish) spots. Because of the restricted root system, plants suffering from aluminum toxicity often show symptoms of drought stress and phosphorus deficiency (stunted growth, dark green foliage, and purplish stems).

Tolerance. Among and within plant species there exists a great deal of genetic variability in sensitivity to aluminum toxicity. Major differences among plants with regard to the sensitivity to aluminum toxicity of such functions as root growth and seed germination (Figure 9.21, *right*) can result in distinctly different natural plant communities flourishing on sites that are nearby but whose soils exhibit different soil pH levels. Agricultural crops that originated in areas dominated by acid soils (such as most humid regions) tend to be less sensitive than species originating in areas of neutral to alkaline soils (such as the Mediterranean region). Fortunately, plant breeders have been able to find genes that confer tolerance to aluminum even in species that are typically sensitive to this toxicity (Figure 9.23). Most Al-tolerant plants avoid the problem by excluding aluminum from their roots. To do this, some species raise the pH of the soil just outside the root, causing the aluminum to precipitate. Others excrete organic mucilage that complexes with the aluminum, preventing its uptake into the root. Still others produce certain organic acids that combine with the aluminum to form nontoxic compounds (see Section 9.9).

Manganese, Hydrogen, and Iron Toxicity to Plants

Manganese Toxicity. Although not as widespread as aluminum toxicity, **manganese toxicity** is a serious problem for plants in acid soils derived from manganese-rich parent minerals. Unlike Al, Mn is an essential plant nutrient (see Section 15.5) that is toxic only when taken up in excessive quantities. Like aluminum, manganese becomes increasingly soluble as pH drops, but in the case of Mn, toxicity is common at pH_{water} levels as high as 5.6 (about 0.5 units higher than for aluminum).

Plant species and genotypes within species vary widely with regard to their susceptibility to manganese toxicity. Symptoms of Mn toxicity vary among plant species, but often include crinkling or cupping of leaves and interveinal patches of chlorotic tissue. Unlike for Al, the leaf tissue content of Mn usually correlates with toxicity symptoms, toxicity beginning at levels that range from 200 mg/kg in sensitive plants to over 5000 mg/kg in tolerant plants. Figure 9.22 (*right*) illustrates a case in which low soil pH induced plant uptake of Mn to toxic levels.

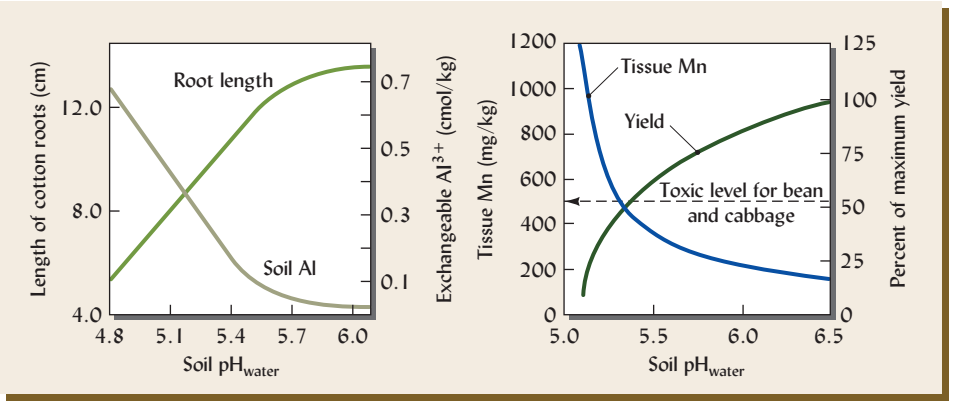

Figure 9.22 *Plant responses to toxicity of aluminum* (left) *and manganese* (right) *at low soil pH.* (Left) *As soil* pH_{water} *drops below 5.2, exchangeable Al increases and cotton root length is severely restricted in an Ultisol.* (Right) *Plant shoot growth (the average of bean and cabbage) declines and Mn content of foliage increases at low pH levels in manganese-rich soils from East Africa (average data for an Andisol and an Alfisol).* [(Left) From Adams and Lund (1966); (right) Redrawn from data in Weil (2000)]

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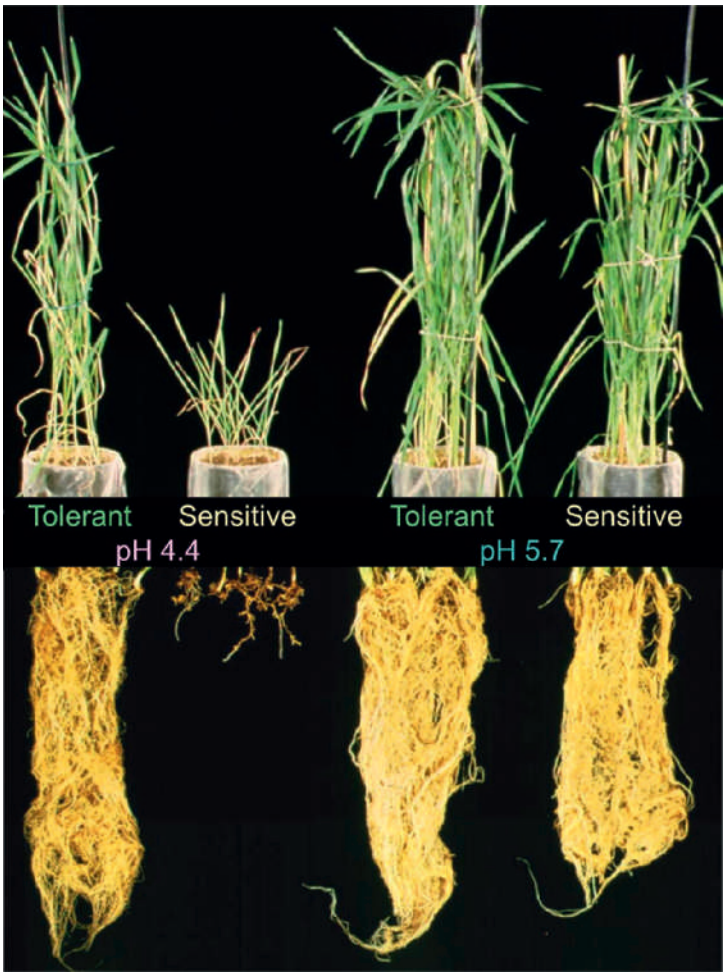

Figure 9.23 *Influence of pH on the growth of shoots (a) and roots (b) from two wheat varieties, one sensitive and one tolerant to aluminum. Note the stunted shoot growth and extremely stunted, stubby root system of the sensitive variety in the low-pH treatment.* (Photos courtesy of C. D. Foy, USDA/ARS, Beltsville, MD)

Since the reduced form [Mn(II)] is far more soluble than the oxidized form [Mn(IV)], toxicity is greatly increased by low oxygen conditions associated with a combination of oxygen-demanding, decomposable organic matter and wet conditions. Manganese toxicity is also common in certain high organic matter surface horizons of volcanic soils (e.g., Melanudands). Unlike for Al, the solubility and toxicity of Mn are commonly accentuated, rather than restricted, by higher soil organic matter (Table 9.2).

Hydrogen Ion Toxicity. At pH levels below 4.0–4.5, the H^+ ions themselves are of sufficient concentration to be toxic to some plants, mainly by damaging the root membranes. Likewise, such low pH, even in the absence of high Al or Mn, has been found to kill certain beneficial soil bacteria such as the *Rhizobium* bacteria that help supply legume plants with nitrogen (see Section 13.11).

Iron Toxicity. Iron can become toxic to plants in the oxidized form at very low pH levels (usually less than 4.0). Anaerobic conditions combined with acid pH can cause toxicity of iron in the reduced Fe(II) form, which is far more soluble than the oxidized form. Such iron toxicity can be a problem in acid rice paddies. Again, plant species and strains vary widely with regard to their susceptibility to iron toxicity.

Nutrient Availability to Plants

Figure 9.24 shows in general terms the relationship between the pH of mineral soils and the availability of plant nutrients and aluminum. Note that in strongly acid soils the availability of the macronutrients (Ca, Mg, K, P, N, and S) as well as the two micronutrients, Mo and B,

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Table 9.2
RELATIONSHIP BETWEEN SOIL PROPERTIES ASSOCIATED WITH ACIDITY AND SURVIVAL OF SUGAR MAPLE SEEDLINGS

Data are averages for 18 forested sites dominated by overstory sugar maples. Al was most abundant in the low-organic-matter B horizons and Mn most abundant in the high-organic-matter O horizons. The critical ratio associated with tree mortality of Ca/Al <1.0 occurred only in the B horizons, while the critical ratio of Ca/Mn <30 occurred in all horizons and was especially low in the highly organic O horizons.

	Exchangeable cations, mg/kg			Ratio, mol_c/mol_c		
Seedlings present?	Mn	Ca	Al	Ca/Al	Ca/Mn	Soil pH_{water}
O Horizons						
No	188	2738	53	23.1	**20**	4.02
Yes	89	6371	38	74.1	98	4.45
A Horizons						
No	59	1252	143	3.9	28	4.34
Yes	33	2755	142	8.5	114	4.58
B Horizons						
No	15	305	279	0.5	28	4.62
Yes	8	1061	202	2.3	180	4.90

[Data from Demchik et al. (1999b)] Ca/Al and Ca/Mn ratios calculated here to give units shown.

is curtailed. In contrast, availability of the micronutrient cations (Fe, Mn, Zn, Cu, and Co) is increased by low soil pH, even to the extent of toxicity.

In slightly to moderately alkaline soils, molybdenum and all of the macronutrients (except phosphorus) are amply available, but levels of available Fe, Mn, Zn, Cu, and Co are so low that plant growth is constrained. Phosphorus and boron availability is likewise reduced in alkaline soil—commonly to a deficiency level.

It appears from Figure 9.24 that the pH range of 5.5–7.0 may provide the most satisfactory plant nutrient levels overall. However, this generalization may not be valid for all soil and plant combinations. For example, certain micronutrient deficiencies are common in some plants when sandy mineral soils are limed to pH values of only 6.5–7.0. Also, in organic-rich soils such as peats, forest O horizons, and many potting mixes, the pH for optimal nutrient availability is about 1 full unit lower and aluminum toxicity is not a problem.

Microbial Effects

Fungi are particularly versatile, flourishing satisfactorily over a wide pH range. Fungal activity tends to predominate in low pH soils because bacteria are strong competitors and tend to dominate the microbial activity at intermediate and higher pH. Individual microbial species exhibit pH optima that may differ from this generality, but bacterial communities tend to be less active and less diverse in strongly acid soils (Figure 9.25). Manipulation of soil pH can alter microbial communities and help control certain soilborne plant diseases (see Section 11.13)

Optimal pH Conditions for Plant Growth

Plants vary considerably in their tolerance to acid and/or alkaline conditions (Figure 9.26). For example, certain legume crops such as alfalfa and sweet clover grow best in near-neutral or alkaline soils, and most humid-region mineral soils must be limed to grow these crops satisfactorily. Asparagus and cantaloupe are two food crops that have a high calcium requirement and grow best at pH levels near or above 7.0.

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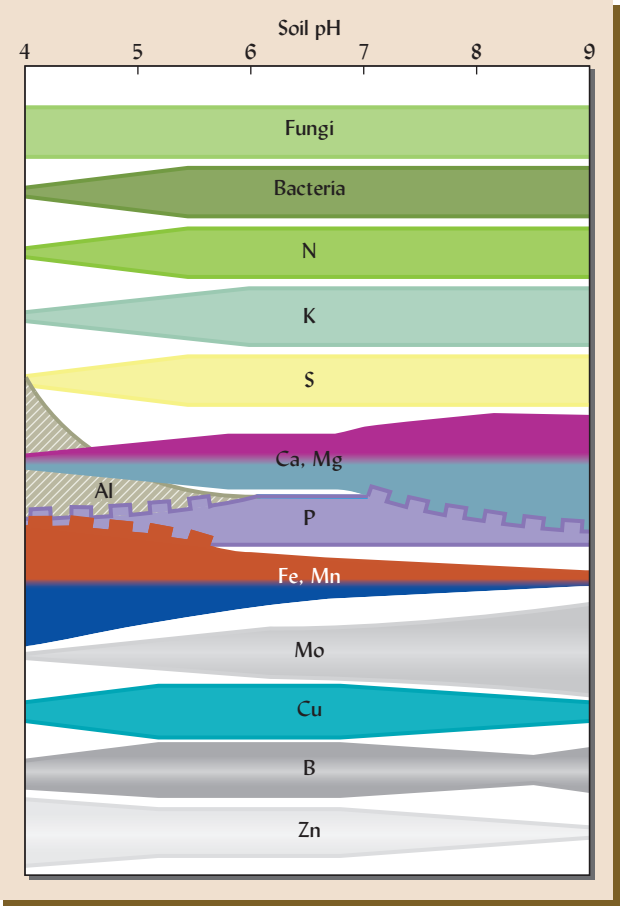

Figure 9.24 *Relationships existing in mineral soils between pH and the availability of plant nutrients. The relationship with activity of certain microorganisms is also indicated. The width of the bands indicates the relative microbial activity or nutrient availability. The jagged lines between the P band and the bands for Ca, Al, and Fe represent the effect of these metals in restraining the availability of P. When the correlations are considered as a whole, a pH range of about 5.5 to perhaps 7.0 seems to be best to promote the availability of plant nutrients. In short, if the soil pH is suitably adjusted for phosphorus, the other plant nutrients, if present in adequate amounts, will be satisfactorily available in most mineral soils. In organic-rich soils such as peats, forest O horizons and many potting mixes, the pH for optimal nutrient availability is about 1 full unit lower and Al is not a problem.* (Diagram courtesy of N. C. Brady and Ray R. Weil)

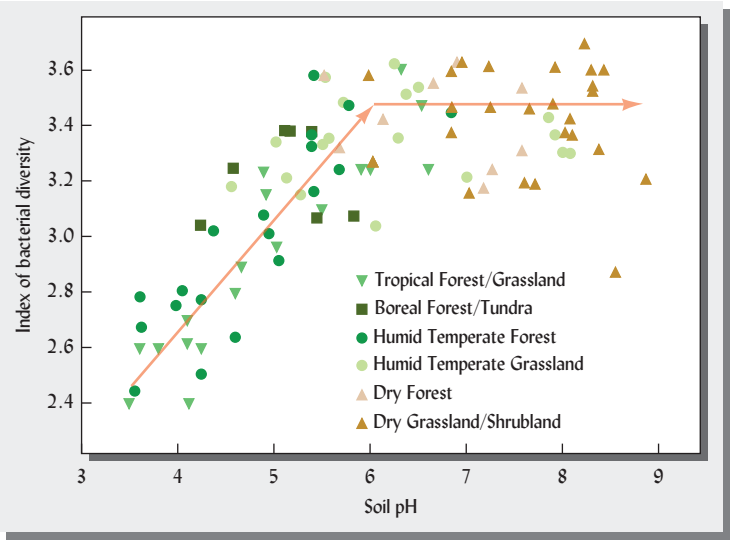

Figure 9.25 *Soil pH greatly influences the diversity of bacteria. In 98 different ecosystems in North and South America, ribosomal DNA fingerprinting was used to estimate the diversity of the bacterial communities. The index of diversity was high in soils with* pH_{water} *above 6, but was much reduced by more acid soil conditions. Fungal diversity was not studied here, but could be expected to show the opposite trend.* [Modified from Fierer and Jackson (2006)]

Because forests exist mainly in humid regions where acid soils predominate, many forest plants are at the opposite end of the scale. Forest species such as rhododendrons, azaleas, blueberries, larch, some oaks, and most pines are inefficient in taking up the iron they need. Since high soil pH and high calcium saturation reduce the availability of iron, these plants will show iron deficiency **chlorosis** (yellowing of the interveinal part of the newest leaves) under these soil conditions (see Section 15.7). Even forest trees differ in their tolerance of soil acidity

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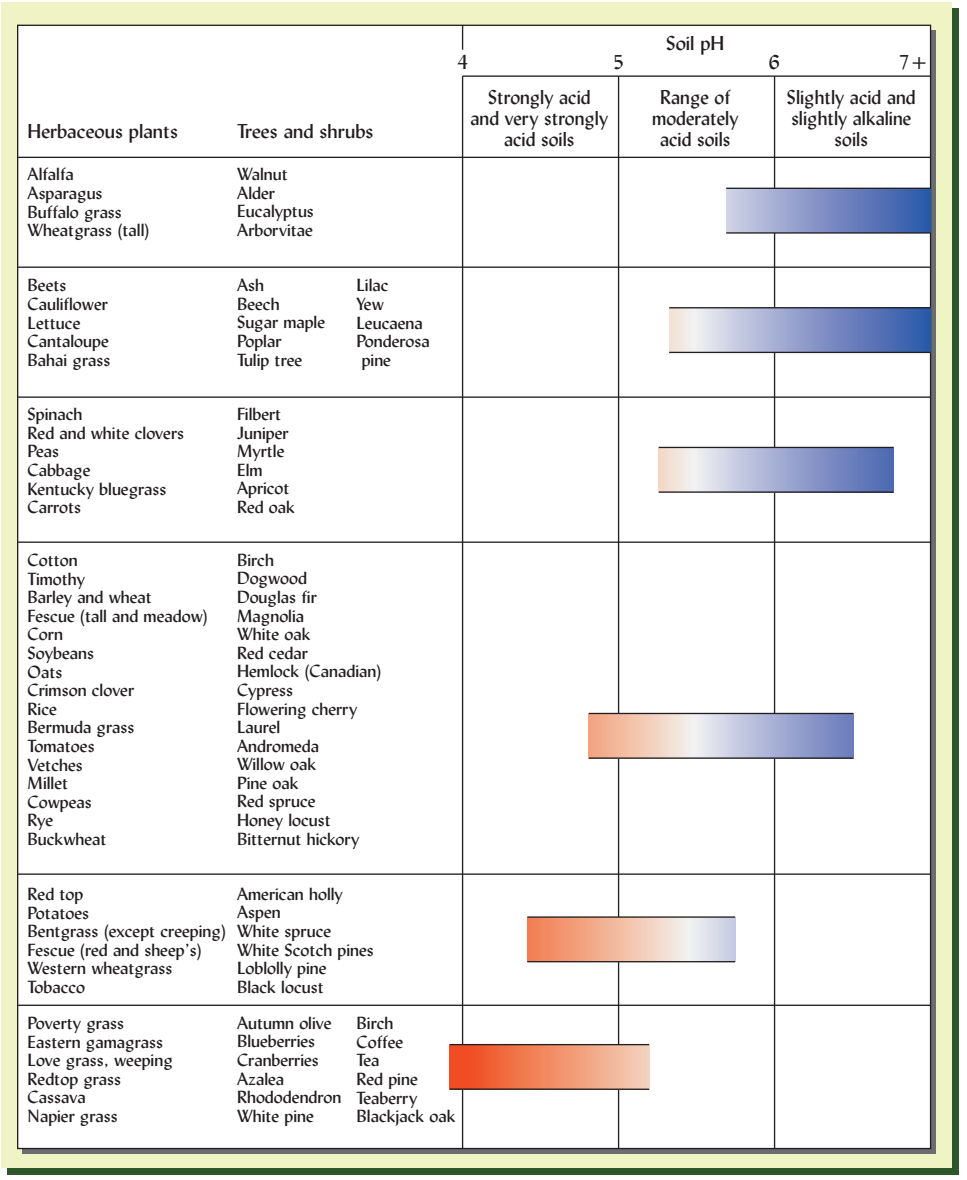

Figure 9.26 *Ranges of pH in mineral soils that present appropriate conditions for optimal growth of various plants. Note that the pH ranges are quite broad, but that plant requirement for calcium and sensitivity to aluminum toxicity generally decreases from the top group to the bottom group. Other factors, such as fertility level, will influence the actual relationships between plant growth and soil pH in specific cases. However, this chart may help in choosing which species to plant or when deciding whether to change the pH with soil amendments.*

and high aluminum (Table 9.3). For example, elm, poplar, honey locust, and the tropical legume tree *Leucaena* are known to be less tolerant to acid soils than are many other forest species.

Most cultivated crop plants (except those such as sweet potato, cassava, and others that originated in the humid tropics) grow well on soils that are just slightly acid to near neutral. Therefore, for most grain and vegetable crops a soil pH in the range of perhaps 5.5–7.0 is most suitable.

Soil pH and Organic Molecules

Soil pH influences environmental quality in many ways, but we will discuss only one example here—the influence of pH on the mobility of ionic organic molecules in soils. The molecular structure of certain ionic herbicides includes such chemical groups as $-NH_2$ and $-COO^-$. If soil pH is low, the excess H^+ ions (protons) present in solution are attracted to and bond with these chemical groups, neutralizing negative charges and creating positively charged sites on the molecule. This process is called ***protonation.***

Atrazine, a chemical that is widely used to control weeds in corn fields, is an example of a chemical whose mobility is greatly influenced by soil pH. In a low pH environment, the atrazine molecule protonates, developing a positive charge. The positively charged molecule is

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Table 9.3
FOREST SPECIES RESPONSE TO CALCIUM OXIDE ON AN EXTREMELY ACID SOIL
Adding 1 g of CaO to 180 g of this soil (a Dystrudept in Pennsylvania) raised the pH from 3.8 to 6.8 and the Ca/Al ratio from 0.24 to 15.5. The treated soil was overlimed with respect to such acid-loving species as Teaberry, White pine, and Chestnut oak which were among trees showing reduced growth at the higher pH.

Positive response to CaO (Al-sensitive)		Negative or no response to CaO	
Plant species	Root response to CaO addition, %	Plant species	Root response to CaO addition, %
Sugar maple	+150	Black locust	0
Pin oak	+104	Mountain laurel	−15
Quaking aspen	+83	Blueberry	−21
Bitternut hickory	+52	Norway spruce	−31
Red cedar	+46	Black birch	−47
Grey dogwood	+41	Chestnut oak	−52
White spruce	+40	White pine	−53
Honey locust	+17	Teaberry	−68

[Data selected from Demchik et al. (1999a)]

then adsorbed on the negatively charged soil colloids, where it is held until it can be decomposed by soil organisms (see also Figures 8.37–8.39). The adsorbed pesticide is less likely to move downward and into the groundwater. At pH values above 5.7, however, the adsorption is greatly reduced, and the tendency for the herbicide to move downward in the soil is increased. Of course, the adsorption in acidic soils also reduces the availability of atrazine to weed roots, thus reducing its effectiveness as a weed killer. Farmers using such chemicals may notice excessive weediness in their fields as the first sign that their soils need liming.

9.8 RAISING SOIL pH BY LIMING

Agricultural Liming Materials

To decrease soil acidity (raise the pH), the soil is usually amended with alkaline materials that provide conjugate bases of weak acids. Examples of such conjugate bases include carbonate (CO_3^{2-}), hydroxide (OH^-), and silicate (SiO_3^{2-}). These conjugate bases are anions that are capable of consuming (reacting with) H^+ ions to form weak acids (such as water). For example:

$$CO_3^{2-} + 2H^+ \longrightarrow CO_2 + H_2O \tag{9.21}$$

Most commonly, these bases are supplied in their calcium or magnesium forms ($CaCO_3$, etc.) and are referred to as **agricultural limes**. Some liming materials contain oxides or hydroxides of alkaline earth metals (e.g., CaO or MgO), which form hydroxide ions in water.

$$CaO + H_2O \longrightarrow Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^- \tag{9.22}$$

Unlike fertilizers, which are used to supply plant nutrients in relatively small amounts for plant nutrition, *liming materials are used to change the chemical makeup of a substantial part of the root zone.* Therefore, lime must be added in large enough quantities to chemically react with a large volume of soil. This requirement dictates that inexpensive, plentiful materials are normally used for liming soils—most commonly finely ground limestone or materials derived from it (see Table 9.4). Wood ashes (which contain oxides of Ca, Mg, and K) are also effective. As a practical matter, the choice of which liming material to use is often based mainly on the relative costs of transporting large amounts of these materials from their source to the site to be limed.

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Table 9.4
COMMON LIMING MATERIALS: THEIR COMPOSITION AND USE
The two limestones are by far the most commonly used. Use of the other materials is largely dependent on the need for fast reaction, cost, and local availability. The relative amounts needed of the different materials can be judged by comparing the respective $CaCO_3$ equivalent values.

Common name of liming material	Chemical formula (of pure materials)	% $CaCO_3$ equivalent	Comments on manufacture and use
Calcitic limestone	$CaCO_3$	100	Natural rock ground to a fine powder. Low solubility; may be stored outdoors uncovered. Noncaustic, slow to react.
Dolomitic limestone	$CaMg(CO_3)_2$	95–108	Natural rock ground to a fine powder; somewhat slower reacting than calcitic limestone. Supplies Mg to plants.
Burned lime (oxide of lime)	CaO (+ MgO if made from dolomitic limestone.)	178	Caustic, difficult to handle, fast-acting, can burn foliage, expensive. Made by heating limestone. Protect from moisture.
Hydrated lime (hydroxide of lime)	$Ca(OH)_2$ (+ $Mg(OH)_2$ if made from dolomitic limestone.)	134	Caustic and difficult to handle. Fast-acting, can burn foliage, expensive. Made by slaking hot CaO with water. Protect from moisture.
Basic slag	$CaSiO_3$	70–90	By-product of pig-iron industry. Must be finely ground. Also contains 1–7% P.
Marl	$CaCO_3$	40–70	Usually mined from shallow coastal beds, dried, and ground before use. May be mixed with soil or peat.
Wood ashes	CaO, MgO, K_2O, K(OH), etc.	40–80	Caustic, fast-acting, water-soluble so must be kept dry during storage.
Misc. lime-containing by-products	Usually $CaCO_3$ with various impurities	20–100	Variable composition; test for toxic impurities.

Dolomitic limestone products should be used if soil magnesium levels are low. In some highly weathered soils, small amounts of lime may improve plant growth, more because of the enhanced calcium or magnesium nutrition than from a change in pH.

How Do Liming Materials React to Raise Soil pH?

Chemical Reactions. Most liming materials—whether they be oxide, hydroxide, or carbonate—react with carbon dioxide and water to yield bicarbonate when applied to an acid soil. The carbon dioxide partial pressure in the soil, usually several hundred times greater than that in atmospheric air, is generally high enough to drive such reactions to the right. For example:

$$\underset{\text{Dolomitic limestone}}{CaMg(CO_3)_2} + 2H_2O + 2CO_2 \rightleftharpoons \underset{\text{Bicarbonate}}{Ca + 2HCO_3^-} + \underset{\text{Bicarbonate}}{Mg + 2HCO_3^-} \qquad (9.23)$$

The Ca and Mg bicarbonates are much more soluble than are the carbonates, so the bicarbonate formed is quite reactive with the exchangeable and residual soil acidity. The Ca^{2+} and Mg^{2+} replace H^+ and Al^{3+} on the colloidal complex:

$$\boxed{\text{Clay or humus}}\begin{matrix}H^+\\Al^{3+}\end{matrix} + \underset{\text{Bicarbonate}}{2Ca^{2+} + 4HCO_3^-} \rightleftharpoons \boxed{\text{Clay or humus}}\begin{matrix}Ca^{2+}\\Ca^{2+}\end{matrix} + \underset{\text{(solid)}}{Al(OH)_3} + H_2O + 4CO_2\uparrow \qquad (9.24)$$

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$$\boxed{\text{Clay or humus}}\begin{matrix}H^+\\Al^{3+}\end{matrix} + \underset{\substack{\text{Limestone}\\\text{(calcite)}}}{2CaCO_3} + H_2O \rightleftharpoons \boxed{\text{Clay or humus}}\begin{matrix}Ca^{2+}\\Ca^{2+}\end{matrix} + \underset{\text{(solid)}}{Al(OH)_3} + 2CO_2\uparrow \tag{9.25}$$

The insolubility of $Al(OH)_3$, the weak dissociation of water, and the release of CO_2 gas to the atmosphere all pull these reactions to the right. In addition, the adsorption of the calcium and magnesium ions lowers the percentage acid saturation of the colloidal complex, and the pH of the soil solution increases correspondingly. The reactions just discussed also point out the important fact that much of the carbon in limestone applied to acid soils will eventually end up in the atmosphere as CO_2. As a result, agricultural liming contributes significantly to the carbon dioxide emissions responsible for anthropogenic climate change.

Silicates can be used as liming materials that do not contain carbon and therefore do not release CO_2 into the atmosphere when they react with acid soils. The most commonly used silicates are calcium silicate from blast furnace slag (a byproduct of steel making) and naturally occurring minerals such as Wollastonite (see Section 15.3). The calcium silicates increase soil pH by consuming H^+ ions and replacing acid cations with Ca^{2+} ions on the exchange complex:

$$CaSiO_3 + H_2O + \text{Colloid-}H^+ \rightarrow \text{Colloid-}Ca^{2+} + H_4SiO_4 \tag{9.26}$$

Lime Requirement: How Much Lime Is Needed to Do the Job?

The amount of liming material required to ameliorate acid soil conditions is determined by several factors, including: (1) the change required in the pH or exchangeable Al saturation, (2) the buffer capacity of the soil, (3) the amount or depth of soil to ameliorate, (4) the chemical composition of the liming materials to be used, and (5) the fineness of the liming material.

Because of greater buffering capacity, the lime requirement for a clay loam is much higher than that of a sandy loam with the same pH value (see Figure 9.27 and Section 9.4).

Within the pH range of 4.5–7.0, the pH change induced by adding lime to an acid soil is determined by the buffering capacity of the particular soil (Figure 9.8). In turn, the capacity to buffer pH is reflected in the CEC and closely related to organic matter and clay contents. Therefore, a titration curve (such as the two examples shown in Figure 9.8) make it possible to estimate approximate amount of liming material needed to raise the soil pH to a desired (see Box 9.4).

Buffer pH Methods for Lime Requirement. A simpler and less expensive lab approach to estimating lime requirements is to equilibrate a soil sample with a special salt solution that has a known initial pH value and is buffered to resist change in pH. For example, the SMP

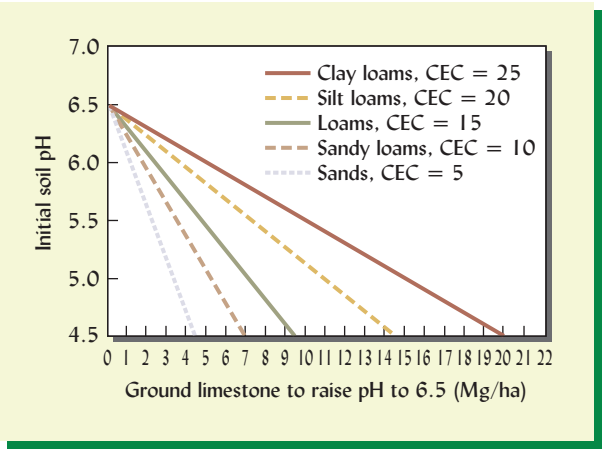

Figure 9.27 *Effect of soil textural class on the amount of limestone required to raise the pH of soils from their initial level to pH 6.5. Note the very high amounts of lime needed for fine-textured soils that are strongly buffered by their high levels of clay, organic matter, and CEC. The chart is most applicable to soils in cool, humid regions where 2:1 clays predominate. In warmer regions where organic matter levels are lower and clays provide less CEC, the target pH would likely be closer to 5.8 and the amounts of lime required would be one-half to one-third of those indicated here. In any case, it is unwise to apply more than 7–9 Mg/ha (3–4 tons/acre) of liming materials in a single application. If more is needed, subsequent applications can be made at 2- to 3-year intervals until the desired pH is achieved.*

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BOX 9.4

CALCULATING LIME NEEDS BASED ON pH BUFFERING

Your client wants to grow a high-value crop of asparagus in a 2-ha field. The soil is a sandy loam with a current pH of 5.0. Asparagus is a calcium-loving crop that requires a high pH for best production (see Figure 9.26), so you recommend that the soil pH be raised to 6.8. Since the soil texture is a sandy loam, we will assume that its buffer curve is similar to that of the moderately buffered soil B in Figure 9.8. In actual practice, a soil test laboratory using this method to calculate the lime requirement should have buffer curves for the major types of soils in its service area.

1. Extrapolating from curve B in Figure 9.8, we estimate that it will require about 2.5 cmolc of lime/kg of soil to change the soil pH from 5.0 to 6.8. (Draw a horizontal line from 5.0 on the y-axis of Figure 9.8 to curve B, then draw a vertical line from this intersection down to the x-axis. Repeat this procedure beginning at 6.8 on the y-axis. Then use the x-axis scale to compare the distance between where your two vertical lines intersect the x-axis.)
2. Each molecule of $CaCO_3$ neutralizes 2 H^+ ions:

$$CaCO_3 + 2H^+ \rightarrow \rightarrow Ca^{2+} + CO_2 + H_2O$$

3. The mass of 2.5 cmolc of pure $CaCO_3$ can be calculated using the molecular weight of $CaCO_3$ = 100 g/mol:

$$(2.5\ \text{cmol}_c\ CaCO_3/\text{kg soil}) \times (100\ \text{g/mol}\ CaCO_3) \times (1\ \text{mol}\ CaCO_3/2\ \text{mol}_c) \times (0.01\ \text{mol}_c/\text{cmol}_c) = 1.25\ \text{g}\ CaCO_3/\text{kg soil}$$

4. Using the conversion factor of 2×10^6 kg/ha of surface soil, we calculate the amount of pure $CaCO_3$ needed per hectare:

$$(1.25\ \text{g}\ CaCO_3/\text{kg soil}) \times (2 \times 10^6\ \text{kg soil/ha}) = 2{,}500{,}000\ \text{g}\ CaCO_3/\text{ha}$$

$$(2{,}500{,}000\ \text{g}\ CaCO_3/\text{ha}) \times (1\ \text{kg}\ CaCO_3/1000\ \text{g}\ CaCO_3) = 2500\ \text{kg}\ CaCO_3/\text{ha}$$

$$2500\ \text{kg}\ CaCO_3/\text{ha} = 2.5\ \text{Mg/ha (or about 1.1 tons/acre)}$$

5. Since our limestone has a $CaCO_3$ equivalence of 90%, 100 kg of our limestone would be the equivalent of 90 kg of pure $CaCO_3$. Consequently, we must adjust the amount of our limestone needed by a factor of 100/90:

$$2.5\ \text{Mg pure}\ CaCO_3 \times 100/90 = 2.8\ \text{Mg limestone/ha}$$

6. Finally, because not all the $CaCO_3$ in the limestone will completely react with the soil, the amount calculated from the laboratory buffer curve is usually increased by a factor of 2:

$$(2.8\ \text{Mg limestone/ha}) \times 2 = 5.6\ \text{Mg limestone/ha}$$

(using Appendix B, this value can be converted to about 2.5 tons/acre)

Note that this result is very similar to the amount of lime indicated by the chart in Figure 9.27 for this degree of pH change in a sandy loam:

$$5\ \text{cmol}_c/\text{kg} \times (100\ \text{g/mol}\ CaCO_3) \times (1\ \text{mol}\ CaCO_3/2\ \text{mol}_c) \times (0.01\ \text{mol}_c/\text{cmol}_c) = 2.5\ \text{g}\ CaCO_3/\text{kg soil.}$$

This amount is equivalent to 5000 kg/ha (2.5 g/kg × 2×10^6 kg/ha). Experience suggests that to assure a complete reaction in the field, the amount of limestone so calculated must be multiplied by a factor of 1.5 or 2.0 to give the actual amount of lime to apply.

(Shoemaker et al., 1961) buffer method is widely used for moderately weathered soils with high CEC values. Also popular is the Adams-Evans (Adams and Evans, 1962) solution, which is designed for use with lower CEC Ultisols and Oxisols.

For all such methods, the greater the total acidity of the soil, the more the solution's buffering is overcome. Therefore, the pH *drop* in the buffer solution equilibrated with a soil is proportional to the amount of lime that would be needed to raise the pH of that soil. The amount of lime required to make a desired change in pH is determined from empirical equations that describe this proportionality as it pertains to the type of soils in question. The important thing to remember is that *the buffer pH indicates how much the soil acidity was able to change the test solution pH, but is not a measure of the soil pH itself.* For example, in the soil test report depicted in Figure 16.48, the soil pH_{water} = 5.2, in the very acid range, but the Adams-Evans buffer pH = 7.63, only slightly lowered from the initial pH of 8.0; therefore a relatively small application of lime was recommended (1 ton/acre = 2.2 Mg/ha).

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Exchangeable Aluminum. Liming to eliminate exchangeable aluminum, rather than to achieve a certain soil pH, has been found appropriate for highly weathered soils such as Ultisols and Oxisols. By this approach, the required amount of lime can be calculated using values for the initial CEC and the percent Al saturation. For example, if a soil has a CEC of 10 $cmol_c$/kg and is 50% Al-saturated, then 5 $cmol_c$/kg of Al^{3+} ions must be displaced (and their acidity from Al hydrolysis neutralized). This would require 5 $cmol_c$/kg of $CaCO_3$:

Influence of Lime Composition, Fineness, and Depth of Incorporation. Liming materials are usually sold and rates for their application recommended on the basis of pure CaO or $CaCO_3$. The general values in Table 9.4 suggest, for example, that a recommendation for 1.0 Mg of $CaCO_3$ equivalent could be met by using either 0.56 Mg of burned lime (1.0/1.78 = 0.56) or 1.43 Mg of basic slag (1.0/0.7 = 1.43). In addition, for limestone, materials should be ground finely so at least 50% of the particles can pass through a 60-mesh screen (smaller than 0.25 mm in diameter). Coarsely ground limestone reacts so slowly with the soil as to have little ameliorating effect on soil acidity. Finally, the recommendation must be adjusted if the depth of incorporation is other than that assumed or specified. In the example just given, if the recommendation was for incorporation to 18 cm, but you plan to incorporate to only 9 cm, then half as much liming material should be used.

How Lime Is Applied

Frequency. Liming materials slowly react with soil acidity, gradually raising the pH to the desired level over a period ranging from a few weeks in the case of hydrated lime to a year or so with finely ground limestone. In humid regions the forces of acidification proceed relentlessly and application of lime to arable soils is not a one-time proposition, but must be repeated every 3–5 years (Figure 9.28).

Because of its gradual effects, lime should be spread about 6–12 months ahead of the crop that has the highest pH and calcium requirements. Thus, in a rotation with corn, wheat, and two years of alfalfa, the lime may be applied after the corn harvest to favorably influence the growth of the alfalfa crop that follows. However, since most lime is bulk-spread using heavy trucks (Figure 9.29), applications are most feasible on the sod or hay crop or when soil is dry or frozen.

Depth of Incorporation. Liming will be most beneficial to acid-sensitive plants if as much as possible of the root environment is altered. The Ca^{2+} and Mg^{2+} ions provided by limestone replace acid cations on the exchange complex and do not move readily down the profile. Therefore, for soil with a high CEC, the short-term effects of limestone are mainly limited to the soil layer into which the material was incorporated, usually the upper 15–20 cm.

Since subsoils are low in organic matter, subsoil acidity is often accompanied by Al toxicity causing plant roots to be restricted to the upper, limed surface soil layer. The effects of

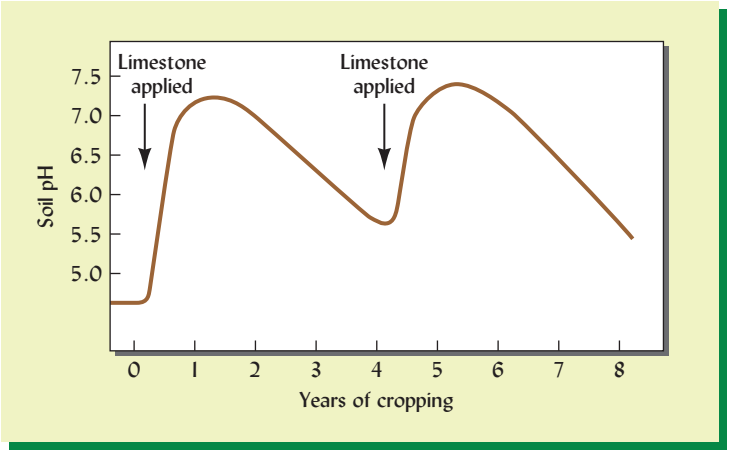

Figure 9.28 *Gradual changes in soil pH in response to liming illustrate why repeated applications of limestone are needed to maintain the appropriate chemical balance in the soil. Soil pH increases during the months after an application of limestone and reaches a peak after about one year. However, the pH gradually declines thereafter until a new application of lime is required.*

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Figure 9.29 *Bulk application by specially equipped trucks is the most widespread method of applying ground limestone. The scene pictured occurred on a windy day and the dispersion by wind illustrates the finely ground nature of the agricultural limestone applied. To avoid problems with heavy trucks bogging down in soft, recently tilled soils, it is often preferred to make lime applications to land that is in sod, under no-till management, or frozen hard.* (Photo courtesy of Ray R. Weil)

subsoil acidity will be especially detrimental during dry periods, when the plants would most benefit if their roots had access to the huge volume of water usually stored in the deeper soil horizons. Heavy plows pulled by large crawler tractors could incorporate lime down to 60 cm deep, but such an operation is usually prohibitively expensive and disruptive of soil quality. It is feasible to create low-acidity zones that roots can use to explore the subsoil by applying lime in deep vertical slots in crop crows or in the planting holes when trees are established. A sustainable alternative may be to encourage the activity of certain species of deep-burrowing earthworms that have been found effective in moving lime down the soil profile. Other alternatives for ameliorating subsoil acidity are discussed in Section 9.9.

Overliming. Another practical consideration is the danger of **overliming**; it is easy to add a little more lime later, but quite difficult to counteract the results of applying too much. The detrimental results of excess lime include deficiencies of iron, manganese, copper, and zinc; reduced availability of phosphate; and constraints on the plant absorption of boron from the soil solution. Overliming is not very common on fine-textured soils with high buffer capacities, but it can occur easily on coarse-textured soils that are low in organic matter. Therefore, liming materials should be added conservatively to poorly buffered soils. For some Ultisols and Oxisols, overliming may occur if the pH is raised even to 6.0.

Special Liming Situations

Liming Forests. It is rarely practical to spreading limestone on forested watersheds (see Section 9.6) as these areas are not accessible to ground-based spreaders, and manual application is too tedious and expensive. In some cases, landowners use helicopters for aerial spreading of small quantities of liming material. For very acid sandy soils, such small applications can ameliorate soil acidity and provide sufficient calcium for the trees.

Untilled Soils. Some soil–plant systems, such as no-till farming, make it difficult to incorporate and mix limestone with the soil. Fortunately, the undisturbed residue mulches in these systems tend to encourage earthworm activity, which, as we have just mentioned, can help distribute lime down the profile. Although apparently not critical on low CEC soils (Figure 9.30), it is considered advisable to incorporate a generous application of limestone as deeply as possible to correct any root-limiting acidity before commencing a no-till system on an acid high-CEC soil. Subsequent surface applications of limestone should adequately combat the acidity, which forms near the surface due to the decomposition of residues and the application of nitrogen fertilizers.

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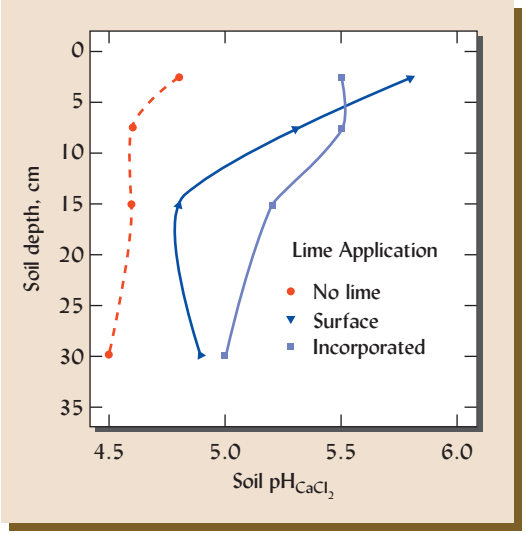

Figure 9.30 *Soil pH 5 years after lime was applied to the soil surface or incorporated in preparation for converting grass pasture to no-till cropland. Dolomitic limestone was applied at 4.5 Mg/ha, enough to eliminate exchangeable Al^{3+} in the upper 20 cm of this clayey Oxisol in Brazil. Four months before the first crop was sown, three treatments were established: (1) no lime, (2) lime applied on the soil surface, and (3) lime incorporated into the soil, half plowed down to 20 cm and the remainder harrowed into the upper 10 cm. No other tillage was used during the 5 years of cropping. The incorporated lime raised the pH significantly down to 40 cm, but most markedly in the 20 cm zone of incorporation. The surface-applied lime also raised the pH to a considerable depth, thanks to the earthworm activity and biopore leaching characteristic of pasture soils. Exchangeable Al was negligible at $pH_{CaCl2} > 4.8$. The cumulative crop yield over 5 years was higher where lime was applied, but was not affected by the method of application. Profitability was greatest for the surface-applied lime because no expensive tillage was required (the cost of tillage to incorporate the lime was nearly equal to the cost of the lime itself).* [Graphed from data in Caires et al. (2006)]

In lawns, golf greens, and other turfgrass areas it is also not possible to till the needed limestone into the soil. Again, the time to correct any problems with soil acidity is during soil preparation for the initial establishment of the grass. By proper timing of future liming applications with annual aeration tillage operations that leave openings down into the soil (see Figure 7.17), some downward movement of the lime can be achieved. In untilled systems, which require surface application of lime, frequent application of small quantities is most effective. In orchards, incorporation of lime into the planting hole, followed by periodic surface applications, is recommended for acid soils.

9.9 ALTERNATIVE WAYS TO AMELIORATE THE ILL EFFECTS OF SOIL ACIDITY

Where the principal acidity problem is in the surface horizon and where sources of limestone are readily accessible, traditional liming procedures, as just described, are quite effective and economical. However, where subsoil acidity is a problem or where liming materials are not accessible or affordable, several other approaches to combating the negative effects of soil acidity may be appropriate for use with or without traditional liming. Particularly deserving of attention are the use of gypsum and organic materials to reduce aluminum toxicity and the use of plant species or genotypes that tolerate acid conditions.

Gypsum Applications

Gypsum ($CaSO_4 \cdot 2H_2O$) is a widely available material found in natural deposits or as an industrial by-product from the manufacture of high-analysis fertilizers, from flue-gas desulfurization by air-pollution "scrubbers" and in dry-wallboard wastes from construction or demolition of buildings. Researchers, mainly in Brazil, South Africa, and the southeastern United States, have found that gypsum can ameliorate aluminum toxicity despite the fact that it does not increase soil pH. In fact, gypsum has been found more effective than lime in reducing exchangeable aluminum in subsoils and thereby in improving root growth and crop yields (see Figure 9.31).

One reason for the effectiveness of gypsum is that the calcium from surface-applied gypsum moves down the soil profile more readily than that from lime. As lime dissolves, its reactions raise the pH, thus increasing the pH-dependent charges on the soil colloids, which in turn retain the released Ca^{2+}, preventing its downward leaching. In addition, the anion released by lime is either OH^- or CO_3^{2-}, both of which are largely removed by the lime reactions (either by forming water or carbon dioxide gas), thus depriving the Ca^{2+} cations of surplus anions that could accompany them in the leaching process. By contrast, gypsum as a neutral

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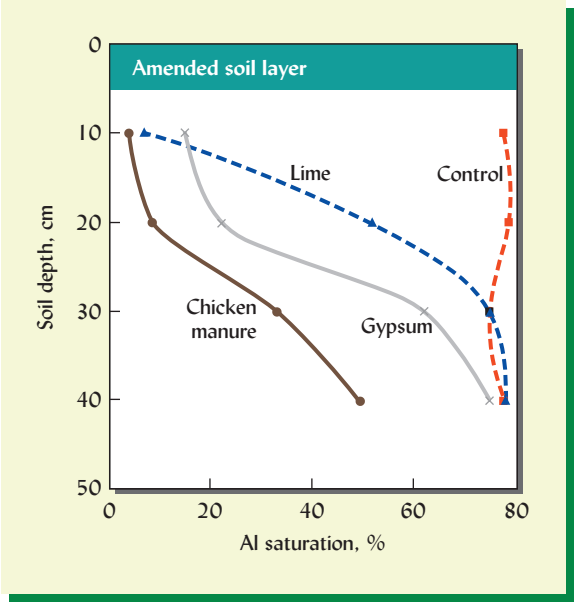

Figure 9.31 *Aluminum saturation percentage in the subsoil of a fine-textured Hawaiian Ultisol after treatment of the surface soil with chicken manure, limestone, or gypsum. The soil was slowly leached with the 380 mm of water. The lime raised the pH and thereby effectively reduced Al saturation, though only in the upper 10–20 cm. The effect of gypsum extended somewhat more deeply. Gypsum does not raise the pH or increase the CEC, but is more soluble than lime and provides the SO_4^{2-} anions to accompany Ca^{2+} cations as they leach downward in solution. The greatest and deepest reduction in Al saturation resulted from the chicken manure. Another Ca-rich organic amendment, sewage sludge, gave similar results (not shown). The manure probably formed soluble organic complexes with Ca^{2+} ions, which then moved down the profile where Ca exchanged with Al to form nontoxic organic Al complexes.* [Redrawn from Hue and Licudine (1999); used with permission of the American Society of Agronomy]

salt does not raise the soil pH and so does not increase the CEC. Furthermore, the SO_4^{2-} anion released by the dissolution of gypsum is available to accompany Ca^{2+} cations in leaching.

Once the Ca^{2+} and SO_4^{2-} ions move down to the subsoil, the mechanisms for amelioration of the effects of acidity may vary from soil to soil. However, gypsum is known to increase the level of calcium and reduce the level of aluminum both in the soil solution and on the exchange complex. The Ca^{2+} ions replace Al^{3+} ions from the exchange site, and the released aluminum is thought to react directly, or indirectly, with the sulfate ion. For example, the SO_4^{2-} can replace certain OH^- ions associated with Fe, Al, oxyhydroxides through reactions such as the following:

$$\boxed{\text{Fe, Al oxyhydroxides}}\begin{matrix}-\text{OH}\\-\text{OH}\end{matrix} + Ca^{2+} + SO_4^{2-} \longrightarrow \boxed{\text{Fe, Al oxyhydroxides}}{=}\,SO_4 + Ca^{2+} + 2OH^- \tag{9.27}$$

The $Ca(OH)_2$ can then react with Al^{3+} ions in the soil solution to form insoluble $Al(OH)_3$, thereby reducing the concentration of the Al^{3+} while increasing that of Ca^{2+}:

$$3\,Ca(OH)_2 + 2Al^{3+} \longrightarrow \underset{\text{(insoluble)}}{2Al(OH)_3} + 3Ca^{2+} \tag{9.28}$$

A second probable mechanism of aluminum detoxification by gypsum is the formation of $AlSO_4^-$ ions which are nonphytotoxic.

Using Organic Matter

Practices such as the application of organic wastes, production of cover crops (see Section 16.2), addition of organic mulch, return of crop residues, and protection of the surface soil from erosion help maintain high levels of organic matter in soil. In so doing they can ameliorate the effects of soil acidity in at least three ways:

1. High molecular weight organic matter can bind tightly with aluminum ions and prevent them from reaching toxic concentrations in the soil solution.
2. Low-molecular-weight organic acids produced by microbial decomposition or root exudation can form soluble complexes with aluminum ions that are nontoxic to plants and microbes. Table 9.5 provides an example of the ameliorating effect of

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Table 9.5
EFFECTS OF ORGANIC RESIDUES AND LIME ON SOIL ACIDITY, SOIL ALUMINUM, SOLUBLE CARBON AND THE GROWTH OF A LEGUME FORAGE PLANT, *DESMODIUM INTORTUM* IN ACID TROPICAL SOILS
Note that the organic material (cowpea leaves) raised the pH only 0.5 unit, but caused a dramatic reduction in the various forms of aluminum in the soil and soil solution, comparable to that caused by the slaked lime. The ash from cowpea leaves was less effective in reducing the aluminum. Only the cowpea leaves raised the amount of oxidizable carbon in solution, which in turn complexed the Al leaving much less in solution than otherwise expected at pH 4.9. The ash and lime each doubled the Desmodium yield, but the cowpea leaves tripled it. The data are means of two soils from Hawaii, USA, an Andisol and an Ultisol.

Soil amendment type	Soil Amendment amount[a]	Soil pH	Exchangeable Al	$\sum$ Inorganic Al ions in solution	Al^{3+} in solution	Oxidizable carbon in solution	Desmodium Shoot dry weight	Desmodium Relative yield
			$cmol_c$/kg soil	— μM —		mM	g/pot	% of max.
Control	None	4.55	2.49	18.25	4.18	0.12	2.86	32
Calcium hydroxide (slaked lime)	4 $cmol_c$ as $Ca(OH)_2$/kg soil	5.35	0.14	2.51	0.02	0.13	6.05	69
Cowpea leaves	10 g ground dry cowpea leaves/kg soil)[a]	4.90	0.73	2.42	0.09	2.67	8.82	100
Cowpea ash	Ash from 10 g dry cowpea leaves/kg soil)	4.95	1.55	8.85	0.62	0.17	5.97	72

Compiled from Hue (2011).
[a]The 10 g dry cowpea leaves contained 0.91 $cmol_c$ as $Ca(OH)_2$. All pots were fertilized with an adequate supply of all nutrients except Ca.

adding decomposable organic material. Figure 9.32 illustrates the dramatic reduction in plant growth where soil erosion has spurred acidification in combination with organic matter loss.

3. Many organic amendments contain substantial amounts of calcium held in organic complexes that leach quite readily down the soil profile. Therefore, if such amendments as legume residues, animal manure, or sewage sludge are high in Ca, they can effectively combat aluminum toxicity and raise Ca and pH levels, not only in the surface soil where they are incorporated, but also quite deep into the subsoil (see Figure 9.27).

Enhancing these organic matter reactions may be more practical than standard liming practices for resource-poor farmers or those in areas far from limestone deposits. Green manure crops (vegetation grown specifically for the purpose of adding organic matter to the soil) and mulches can provide the organic matter needed to stimulate such interactions and thereby reduce the level of Al^{3+} ions in the soil solution, even if they do not raise the soil pH. Aluminum-sensitive crops can then be grown following the green manure crop. One caution regarding use of organic amendments to ameliorate aluminum toxicity is that the amounts of these materials needed for this purpose may provide nutrients in excess of what is suggested by nutrient management guidelines, potentially polluting water from excessive leaching and runoff losses of nitrogen and phosphorus (see Sections 16.4 and 16.6).

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Figure 9.32 *These corn plants from two areas in the same well-fertilized and irrigated field illustrate the dramatic affect that aluminum toxicity can have on plant growth. The plant on the left produced no grain and was less than one-third the size of the plant on the right, as indicated by the brackets showing the stem diameter. Its root system is stunted, with little root branching and no visible thin white healthy roots. The stunted plant is suffering from aluminum toxicity because of excessively acid soil with reduced organic matter. In contrast to the non-eroded parts of the field where soil pH was 5.8, soil in the eroded spots in the field exhibited pH 4.7, well below the critical level for aluminum toxicity. The eroded soil also had less organic matter content to detoxify the aluminum, as evidenced from the redder, lighter soil color than the less eroded soil on the right.* (Photo courtesy of Ray R. Weil)

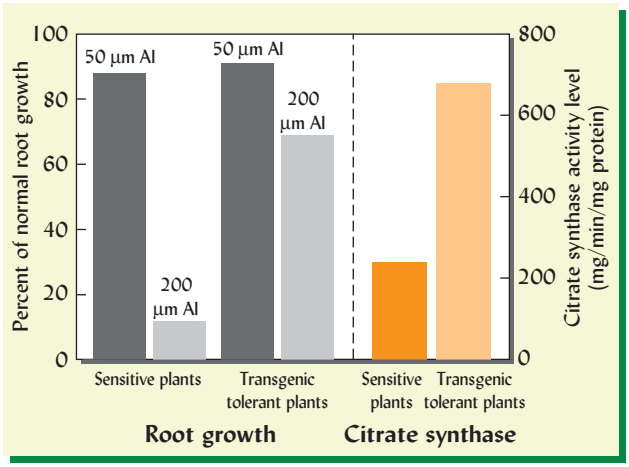

Figure 9.33 (Left) *The effect of two levels of aluminum on the root growth of Al-sensitive plants compared to that of tolerant plants created by transgenic engineering.* (Right) *The comparative production by sensitive and tolerant plants of citrate synthase, an enzyme that stimulates the production of citric acid. Citric acid is produced by roots of tolerant plants to complex with (chelate) Al ions, thus preventing their absorption into the root. High citric acid producing, Al-tolerant strains have been developed by genetic engineering for cassava, maize, and other crops grown in acid tropical soils.* [Drawn from data of de la Fuente et al. (1997)]

Selecting Adapted Plants

Selection of Tolerant Species. It is often more judicious to solve soil acidity problems by changing the plant to be grown rather than by trying to change the soil chemistry. Table 9.3 and Figure 9.26 give some idea of the variation in plant tolerance to soil acidity. The choice of grass and tree species should consider soil pH adaptation, whether revegetating acidic mining debris or landscaping a suburban front yard on alkaline desert soils.

Genetic Improvement of Acid Tolerance. Plant breeders and biotechnologists have developed cultivars that are quite tolerant of very acid conditions (Figure 9.33). For example, high-yielding varieties of wheat, soybeans, and corn that can tolerate soil acidity and high aluminum levels have been developed (see Figure 9.23). These varieties are especially valuable in some areas of the tropics where even modest liming applications are economically impractical. These advances show how collaboration between plant and soil scientists can enhance the ability of low-income families to grow their traditional food crops in acid, degraded soils.

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9.10 LOWERING SOIL pH

It is often desirable to reduce the pH of highly alkaline soils. Furthermore, some acid-loving plants cannot even tolerate soils that are only slightly acid. For example, rhododendrons and azaleas, favorites of gardeners around the world, grow best on soils having pH values of 5.0 and below. Blueberries are an acid-loving crop that requires similar low pH levels for good production. To accommodate such plants, it is sometimes desirable to amend soils with acid-forming organic and inorganic materials (Figure 9.34).

Acid Organic Matter

As organic residues decompose, organic and inorganic acids are formed. These can reduce the soil pH if the organic material is low in calcium and other nonacid cations. Leaf mold from coniferous trees, pine needles, tanbark, pine sawdust, and acid peat are quite satisfactory organic materials to add around ornamental plants (but see Section 12.3 for nitrogen considerations with these materials). However, farm manures (particularly poultry manures), lime-stabilized sewage sludge, and leaf mold of such high-base trees as beech and maple may be alkaline and may increase the soil pH, as discussed in Section 9.9.

Inorganic Chemicals

If nitrogen is needed for fertility, its supply as ammonium sulfate $(NH4)_2SO_4$) will promote rapid acidification. When the addition of large amounts of nitrogen or acid organic matter is not desirable or feasible, inorganic chemicals such as aluminum sulfate ($Al_2(SO_4)_3$) or ferrous sulfate ($Fe^{II}SO_4$) may be used. The latter chemical provides available iron (Fe^{2+} ions) for the plant and, upon hydrolysis, enhances acidity by reactions such as the following:

$$FeSO_4 + \tfrac{1}{4}O_2 + 1\tfrac{1}{2}H_2O \longrightarrow FeOOH + \underset{\text{Sulfuric acid}}{H_2SO_4} \qquad (9.29)$$

Ferrous sulfate thus serves a double purpose for iron-loving plants by supplying available iron directly and by reducing the soil pH—a process that may cause a release of fixed iron present in the soil. Ferrous or aluminum sulfate should be worked into the soil around acid-loving perennial plants, while taking care to avoid overly disturbing the root systems. Contact with ferrous sulfate (but not aluminum sulfate) may cause black discoloration of foliage or mulch from the formation of iron sulfides. Hydrangeas are known for responding to such manipulation of soil acidity by changing the color of their blossoms (Figure 9.35).

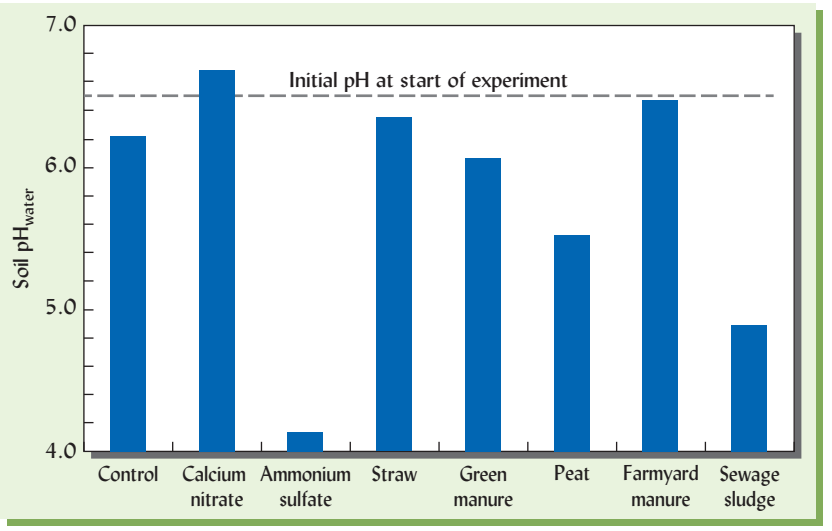

Figure 9.34 *Soil pH levels resulting from annual additions of various materials during a 53-year study on a clay loam soil (Typic Eutrochrept) in Sweden. The initial pH of the soil was 6.5. Low calcium, acid organic materials (peat and sewage sludge) stimulated significant acidification. Ammonium sources of N also acidified the soils (ammonium sulfate fertilizer was applied at 80 kg ha^{-1} yr^{-1}). Sewage sludge also provided much ammonium–N. By contrast, calcium nitrate fertilizer increased the soil pH.* [Graphed from data in Kätterer et al. (2011)]

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Figure 9.35 *Aluminum sulfate was applied to the soil on the left side of this hydrangea bush and lime was applied to the soil on the right side. When the soil pH is below 5.0–5.5 sufficient aluminum is absorbed and combined with the plants anthocyanin pigment to form a bright blue color in the blossoms (especially the large showy sepals surrounding each tiny flower). When the soil pH is 6.0 or above, almost no aluminum is in solution and the plant uses iron in the pigment to produce a pink-colored blossom. White hydrangeas contain no pigment in their sepals, so color changes in their tiny true flowers is not very noticeable.* (Photo courtesy of Ray R. Weil)

Another material often used to increase soil acidity is elemental sulfur (Box 9.5). As the sulfur undergoes microbial oxidation in the soil (see Section 13.20), 2 moles of acidity (as sulfuric acid) are produced for every mole of S oxidized:

$$2S + 3O_2 + 2H_2O \longrightarrow 2H_2SO_4 \tag{9.30}$$

Under favorable conditions, sulfur is 4–5 times more effective, kilogram for kilogram, in developing acidity than is ferrous sulfate. Although ferrous sulfate brings about more rapid plant response, sulfur is less expensive, is easy to obtain, and is often used for other purposes. The quantities of ferrous sulfate or sulfur that should be applied will depend upon the buffering capacity of the soil and its original pH level. Figure 9.8 suggests that for each unit drop in pH desired, a well-buffered soil (e.g., a silty clay loam with 4% organic matter) will require about 4 $cmol_c$ of sulfur per kilogram of soil. This is about 1200 kg S/ha (since 2 mol of H^+ ion are produced by each mole of S oxidized, 1 $cmol_c$ of S = 0.32/2 = 0.16 g).

9.11 CONCLUSION

No other soil characteristic is more important in determining the chemical environment of higher plants and soil microbes than the pH. There are few reactions involving the soil or its biological inhabitants that are not sensitive to soil pH. This sensitivity must be recognized in any soil-management system.

Acidification is a natural process in soil formation that is accentuated in humid regions where processes that produce H^+ ions outpace those that consume them. Natural acidification is largely driven by the production of organic acids (including carbonic acid) and the leaching away of the nonacid cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) that the H^+ ions from the acids displace from the exchange complex. Soil erosion, emissions from power plants and vehicles, as well as inputs of nitrogen into agricultural systems are the principal means by which human activities accelerate acidification. Accelerated acidification is the second only to soil erosion as a globally widespread form of soil degradation.

Aluminum is the other principal acid cation besides hydrogen. Its hydrolysis reactions produce H^+ ions and its toxicity comprises one of the main detrimental effects of soil acidity. The total acidity in soils is the sum of the active, exchangeable (salt replaceable), and residual pools of soil acidity. Changes in the soil solution pH (the active acidity) are buffered by the presence of the other two pools. In certain anaerobic soils and sediments, the presence of reduced sulfur provides the potential for enormous acid production if the material is exposed to air by drainage or excavation.

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BOX 9.5

COSTLY AND EMBARRASSING SOIL pH MYSTERY

Work was nearing completion on an elaborate, 1-ha public garden in the heart of Washington, D.C., USA. A ribbon-cutting ceremony planned for the following week would include the wealthy donors and powerful politicians who had supported the creation of the multimillion-dollar garden. The horticulturalist in charge now paced nervously in the light June rain as half a dozen soil scientists worked feverishly to collect soil and plant samples. Something had gone terribly wrong. Large ugly areas of brown, dying turfgrass were scattered throughout the garden.

Now, after so many rare and exotic trees, shrubs, and flowers had been planted, the horticulturalist feared the worst—the soil might be toxic, need to be removed, and the whole garden started over. The garden was built partly over an underground museum. Beneath the pleasing, undulating surface topography, the "topsoil" lay over a meter thick in places, covering a tangle of pipes, conduits, and wires on the museum roof. If the soil needed to be removed, it would have to be done the slow and expensive way—by hand. The horticulturalist suspected some toxic factor in the soil was killing the grass and would soon start damaging other plants as well. He knew that the growing media installed was not exactly "topsoil" in the usual sense of the word. The landscape design specifications had called for "a natural friable soil . . . with 2% organic content . . . USDA textural class of loam and . . . pH 5.5 to 7.0." The lowest bidder had offered to make a "topsoil" using sediments dredged from a nearby tidal river, modified with enough lime and sand to meet the pH and texture requirements. The consulting engineers had run their lab tests and determined that the material met the specifications.

In late April, as the grand opening date approached, the grass began to turn brown and die in small patches. Although the shrubs, trees, and flowers in the cultivated flower beds were still looking good, the dead patches of turfgrass grew larger with every passing day. Turf specialists were called in, but could find no diseases or pests to account for the dead patches. Now, in desperation, the horticulturalist had hired several soil scientists to check the soil.

Some of the soil scientists knew where the "topsoil" had come from. Those trained as pedologists augured deep, looking in vain for telltale signs of acid sulfate weathering (Section 9.6) they suspected might solubilize toxic aluminum and heavy metals from the river bottom. Others, noting that it was the shallow-rooted turfgrass that seemed to suffer first, went shallow instead of deep (see Box 1.2), obtaining samples from several depths, including a separate set of samples from the topmost 3 cm. They collected pairs of soil samples from several low spot of dead turf and from adjacent high spots where the turf was relatively healthy. Back at the lab, they stirred each soil sample in water and measured the pH. The results were completely normal until they got to the samples of that thin surface layer. Then they couldn't believe their eyes—all the samples of the upper 3 cm from the dead turf areas gave pH readings below pH 3, one as low as pH 1.9 (see bar graph in Figure 9.36). Looking closely at the 0–3 cm cores, they noticed small yellow flecks that smelled like sulfur. The pieces to the puzzle began to fall into place.

What was going on? The previous summer, shortly after the sod had been installed, the horticulturalist had pulled "normal" 20 cm deep soil cores for soil testing (see Section 16.11). The results indicated the soil pH was 7.2, a bit higher than the initial tests and considerably above the pH 6.0–6.5 recommended for the fine fescue turfgrass. Therefore, the horticulturalist had applied about 1000 kg/ha of elemental sulfur powder, as recommended to lower the pH by about 1 unit. He pulled another set of 20 cm deep soil samples about two months later and found the pH was still about 7.0. Therefore, he repeated the sulfur application. The lawn looked healthy during the cool, rainy winter, while the landscapers installed the valuable trees and shrubs. What he had failed to consider was that sufficient time and warm weather would be needed for the soil microorganisms to oxidize the sulfur and produce sulfuric acid to acidify the soil. So the second sulfur application had been an over-response to the normal delay and had doubled the amount of S available to oxidize. Sulfur powder is quite water repellent and buoyant, so rain easily washed much of it off the high areas into the low spots, thus doubling or tripling the already doubled application—giving five or six times the recommended S concentration in those areas. When warm, wet weather the following spring stimulated the S-oxidizing bacteria to go into high gear, extreme acidity was produced in the thin surface layer of soil where the S was located and most of the turfgrass roots proliferated. Thankfully, the remedy would be simple and inexpensive: remove the sod along with about 5 cm of soil and lay down new sod. This they did and everyone at the opening ceremony was impressed by the beautiful lawn and garden.

The lessons learned? (1) Many soil processes are biological in nature—be patient and realize they will respond to environmental conditions with time. (2) Taking deep soil samples may "dilute out" evidence of extreme conditions near the soil surface. Therefore, be sure to sample the upper few cm separately for untilled soils, especially if amendments have been applied to the surface.

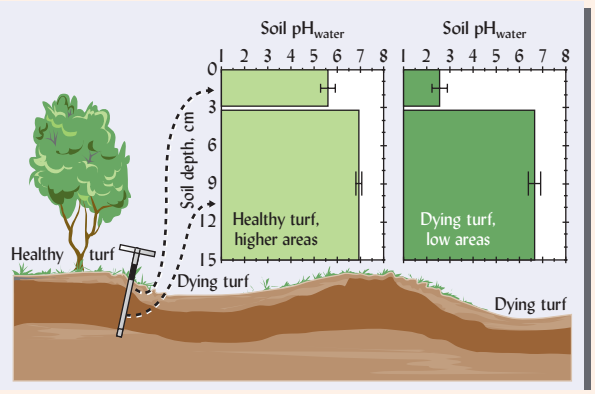

Figure 9.36 *Dying turf and soil acidity in a rooftop garden.* (Courtesy of Ray R. Weil)

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Soil pH is largely controlled by the humus and clay fractions and their associated exchangeable cations. The maintenance of satisfactory soil fertility levels in humid regions depends considerably on the judicious use of lime to balance the losses of calcium and magnesium from the soil. Liming not only maintains the levels of exchangeable calcium and magnesium but in so doing also provides a chemical and physical environment that encourages the growth of most common plants. Gypsum and organic matter (either applied or grown) represent other tools that can be used to ameliorate soil acidity instead of, or in addition to, liming. On the other hand, it is sometimes most judicious to use acid-tolerant plants, rather than attempt to change the chemistry of the soil.

Knowing how pH is controlled, how it influences the supply and availability of essential plant nutrients as well as toxic elements, how it affects higher plants and human beings, and how it can be ameliorated, is essential for the conservation and sustainable management of soils throughout the world. Understanding soil processes that occur at high pH levels is especially important in arid regions, as the next chapter will explain.

STUDY QUESTIONS

1. Soil pH gives a measure of the concentration of H^+ ions in the soil solution. What, if anything, does it tell you about the concentration of OH^- ions? Explain.
2. Describe the role of aluminum and its associated ions in soil acidity. Identify the ionic species involved and the effect of these species on the CEC of soils.
3. If you could somehow extract the soil solution from the upper 16 cm of 1 ha of moist acid soil (pH = 5), how many kg of pure $CaCO_3$ would be needed to neutralize the soil solution (bring its pH to 7.0)? Under field conditions, up to 6 Mg of limestone may be required to bring the pH of this soil layer to a pH of 6.5. How do you explain the difference in the amounts of $CaCO_3$ involved?
4. What is meant by *buffering?* Why is it so important in soils, and what are the mechanisms by which it occurs?
5. What is acid rain, and why does it seem to have greater impact on forests than on commercial agriculture?
6. Calculate the amount of pure $CaCO_3$ that could theoretically neutralize the H^+ ions in a year's worth of acid rain if a 1-ha site received 500 mm of rain per year and the average pH of the rain was 4.0.
7. Discuss the significance of soil pH in determining specific nutrient availabilities and toxicities, as well as species composition of natural vegetation in an area.
8. How much limestone with a $CaCO_3$ equivalent of 90% would you need to apply to eliminate exchangeable aluminum in an Ultisol with CEC = 8 $cmol_c$/kg and an aluminum saturation of 60%?
9. Based on the buffer pH of your soil sample, a lab recommends that you apply 2 Mg of $CaCO_3$ equivalent to your field and plow it in 18 cm deep to achieve your target pH of 6.5. You actually plan to use the lime to prepare a large lawn and till it in only 12 cm deep. The lime you purchase has a carbonate equivalent = 85%. How much of this lime do you need for 2.5 ha?
10. A landscape contractor purchased 10 dump-truck loads of "topsoil" excavated from a black, rich-appearing soil in a coastal wetland. Samples of the soil were immediately sent to a lab to be sure they met the specified properties (silt loam texture, pH 6–6.5) for the topsoil to be used in a landscaping job. The lab reported that the texture and pH were in the specified range, so the topsoil was installed and an expensive landscape of beautiful plants established. Unfortunately, within a few months all the plants began to die. Replacement plants also died. The topsoil was again tested. It was still a silt loam, but now its pH was 3.5. Explain why this pH change likely occurred and suggest appropriate management solutions.
11. A neighbor complained when his azaleas were adversely affected by a generous application of limestone to the lawn immediately surrounding the azaleas. To what do you ascribe this difficulty? How would you remedy it?
12. The ill effects of acidity in subsoils can be ameliorated by adding gypsum ($CaSO_4 \cdot 2H_2O$) to the soil surface. What are the mechanisms responsible for this effect of the gypsum?

REFERENCES

Abedi, M., M. Bartelheimer, and P. Poschlod. 2013. "Aluminium toxic effects on seedling root survival affect plant composition along soil reaction gradients – a case study in dry sandy grasslands." *Journal of Vegetation Science* 24:1074–1085.

Adams, F., and C. E. Evans. 1962. "A rapid method of measuring lime requirement of red-yellow podzolic soils." *Soil Science Society of America Proceedings* 26:355–357.

FOR REFERENCE PURPOSES ONLY

Adams, F., and Z. F. Lund. 1966. "Effect of chemical activity of soil solution aluminum on cotton root penetration of acid subsoils." *Soil Science* **101**:193–198.

Bal, T.L., A.J. Storer, M.F. Jurgensen, P.V. Doskey, and M.C. Amacher. 2015. "Nutrient stress predisposes and contributes to sugar maple dieback across its northern range: A review". *Forestry* 88:64–83

Baldwin, D. 2011. *National Guidance for the Management of Acid Sulfate Soils in Inland Aquatic Ecosystems*. Environment Protection and Heritage Council and the Natural Resource Management Ministerial Council, Canberra. www.rta.nsw.gov.au/environment/downloads/rta_asm_guideline.pdf

Barak, P., B. O. Jobe, A. R. Krueger, L. A. Peterson, and D. A. Laird. 1997. "Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin." *Plant Soil* **197**:61–69.

Blake, L., W. T. Goulding, C. J. B. Mott, and A. E. Johnston. 1999. "Changes in soil chemistry accompanying acidification over more than 100 years under woodland and grass at Rothamsted Experiment Station, UK." *European Journal of Soil Science* **50**:401–412.

Bloom, P. R., U. L. Skyllberg, and M. E. Sumner. 2005. "Soil acidity." In A. Tabatabai and D. Sparks (eds.). *Chemical Processes in Soils*. SSSA Book Series No. 8. Soil Science Society of America, Madison, WI, pp. 411–459.

Caires, E. F., G. Barth, and F. J. Garbuio. 2006. "Lime application in the establishment of a no-till system for grain crop production in southern Brazil." *Soil Tillage Research* **89**:3–12.

Cho, Y., C. Driscoll, C. Johnson, J. Blum, and T. Fahey. 2012. "Watershed-level responses to calcium silicate treatment in a northern hardwood forest." *Ecosystems* **15**:416–434.

de la Fuente et al. 1997. "Aluminum tolerance in transgenic plants by alteration of citrate synthesis." *Science* **276**:1566–1568.

Demchik, M. C., W. E. Sharpe, T. Yangkey, B. R. Swistock, and S. Bubalo. 1999a. "The effect of calcium/aluminum ratio on root elongation of twenty-six Pennsylvania plants." In W. E. Sharpe and J. R. Drohan (eds.). *The Effects of Acidic Deposition on Pennsylvania's Forests*. Proceedings of the Sept. 14–16, 1998 PA Acidic Deposition Conference. Environmental Resources Research Institute, Pennsylvania State University, University Park, PA, pp. 211–217.

Demchik, M. C., W. E. Sharpe, T. Yangkey, B. R. Swistock, and S. Bubalo. 1999b. "The relationship of soil Ca/Al ratio to seedling sugar maple population, root characteristics, mycorrhizal infection rate, and growth and survival." In W. E. Sharpe and J. R. Drohan (eds.). *The Effects of Acidic Deposition on Pennsylvania's Forests*. Proceedings of the Sept. 14–16, 1998 PA Acidic Deposition Conference. Environmental Resources Research Institute, Pennsylvania State University, University Park, PA, pp. 201–210.

Edwards, K. J., P. L. Bond, T. M. Gihring, and J. F. Banfield. 2000. "An archaeal iron-oxidizing extreme acidophile important in acid mine drainage." *Science* **287**:1796–1799.

Falkengren-Grerup, U., D.-J. T. Brink, and J. Brunet. 2006. "Land use effects on soil N, P, C and pH persist over 40–80 years of forest growth on agricultural soils." *Forest Ecology and Management* **225**:74–81.

Fierer, N., and R. B. Jackson. 2006. "The diversity and biogeography of soil bacterial communities." *Proceedings of the National Academy of Science* **103**:626–631.

Greaver, T. L., T. J. Sullivan, J. D. Herrick, M. C. Barber, J. S. Baron, B. J. Cosby, M. E. Deerhake, R. L. Dennis, J.-J. B. Dubois, C. L. Goodale, A. T. Herlihy, G. B. Lawrence, L. Liu, J. A. Lynch, and K. J. Novak. 2012. "Ecological effects of nitrogen and sulfur air pollution in the U.S.: What do we know?" *Frontiers in Ecology and the Environment* **10**:365–372.

Guo, J. H., X. J. Liu, Y. Zhang, J. L. Shen, W. X. Han, W. F. Zhang, P. Christie, K. W. T. Goulding, P. M. Vitousek, and F. S. Zhang. 2010. "Significant acidification in major Chinese croplands." *Science* **327**:1008–1010.

Hoekenga, O. A., and J. V. Magalhaes. 2011. "Mechanisms of aluminum tolerance." In A. Costa de Oliveira and R. K. Varshney (eds.). *Root Genomics*. Springer-Verlag, Berlin, pp. 133–153.

Hue, N. V. 2011. "Alleviating soil acidity with crop residues." *Soil Science* **176**:543–549.

Hue, N. V., and D. L. Licudine. 1999. "Amelioration of subsoil acidity through surface applications of organic manures." *Journal of Environmental Quality* **28**:623–632.

IGBP-DIS. 2000. *Soildata: A Program for Creating Global Soil-Property Databases*. Global Soil Data Task Force, International Geosphere-Biosphere Programme, Data and Information System, Potsdam, Germany. Available from: http://www.daac.ornl.gov

Kätterer, T., M. A. Bolinder, O. Andrén, H. Kirchmann, and L. Menichetti. 2011. "Roots contribute more to refractory soil organic matter than aboveground crop residues, as revealed by a long-term field experiment." *Agriculture Ecosystems and Environment* **141**:184–192.

Kuylenstierna, J. C. I., H. Rodhe, S. Cinderby, and K. Hicks. 2001. "Acidification in developing countries: Ecosystem sensitivity and the critical load approach on a global scale." *Ambio* **30**:20–28.

Lawrence, G. B., H. A. Simonin, B. P. Baldigo, K. M. Roy, and S. B. Capone. 2011. "Changes in the chemistry of acidified adirondack streams from the early 1980s to 2008." *Environmental Pollution* **159**:2750–2758.

Ljung, K., F. Maley, A. Cook, and P. Weinstein. 2009. "Acid sulfate soils and human health-a millennium ecosystem assessment." *Environment International* **35**:1234–1242.

Löfgren, S., N. Cory, T. Zetterberg, P.-E. Larsson, and V. Kronnäs. 2009. "The long-term effects of catchment liming and reduced sulphur deposition on forest soils

FOR REFERENCE PURPOSES ONLY

and runoff chemistry in southwest Sweden." *Forest Ecology and Management* **258**:567–578.

Lumbanraja, J., and V. P. Evangelou. 1991. "Acidification and liming influence on surface charge behavior of Kentucky subsoils." *Soil Science Society of America Journal* **54**:26–34.

Magdoff, F. R., and R. J. Barlett. 1985. "Soil pH buffering revisited." *Soil Science Society of America Journal* **49**:145–148.

Rice, K. C., and J. S. Herman. 2012. "Acidification of earth: An assessment across mechanisms and scales." *Applied Geochemistry* **27**:1–14.

Richter, D. d., Jr. 2007. "Humanity's transformation of earth's soil: Pedology's new frontier." *Soil Science* **172**:957–967.

Ritchey, E.L., D.D. Tyler, M.E. Essington, M.D. Mullen, and A.M. Saxton. 2015. "Nitrogen rate, cover crop, and tillage practice alter soil chemical properties." *Agronomy Journal* 107:1259–1268.

Ryan, P. R., and E. Delhaize. 2012. "Adaptations to aluminum toxicity." In S. Shabala (ed.). *Plant Stress Physiology*. CAB International, London, pp. 171–195.

Shoemaker, H. E., E. O. McLean, and P. F. Pratt. 1961. "Buffer methods for determining lime requirements of soils with appreciable amounts of extractable aluminum." *Soil Science Society of America Proceedings* **25**:274–277.

Stine, M. A., and R. R. Weil. 2002. "The relationship between soil quality and crop productivity across three tillage systems in south central Honduras." *American Journal of Alternative Agriculture* **17**:2–8.

Sullivan, T. J., I. J. Fernandez, A. T. Herlihy, C. T. Driscoll, T. C. McDonnell, N. A. Nowicki, K. U. Snyder, and J. W. Sutherland. 2006. "Acid-base characteristics of soils in the Adirondack mountains, New York." *Soil Science Society of America Journal* **70**:141–152.

Weil, R. R. 2000. "Soil and plant influences on crop response to two African phosphate rocks." *Agronomy Journal* **92**:1167–1175.

Zhang, F., S. Kang, J. Zhang, R. Zhang, and F. Li. 2004. "Nitrogen fertilization on uptake of soil inorganic phosphorus fractions in the wheat root zone." *Soil Science Society of America Journal* **68**:1890–1895.

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10 Soils of Dry Regions: Alkalinity, Salinity, and Sodicity

Alkali has accumulated on them to such an extent that they are mere bogs and swamps and alkali flats, and the once fertile lands are thrown out as ruined and abandoned tracts.
—*Milton Whitney,* First Chief of the Division of Soils, USDA, Bulletin No. 14, 1898

North African Oasis. (Ray R. Weil)

More than 2100 years ago, Roman armies finally emerged victorious in a long and bitter series of wars against their great rival, Carthage, a city-state located on the semiarid north coast of Africa near modern day Tunis. To seal their victory and ensure that the Carthaginians would not arise once more to challenge the supremacy of Rome, the victors not only razed the city itself, but are said to have also *plowed salt into the land* around it. Common table salt (sodium chloride) was the ultimate weapon because it made the lands around Carthage useless for growing the food that would be required by the population (and armies) of a resurgent city-state.

In this chapter, we will learn why high levels of soluble salts can have such detrimental effects on soils and how for centuries people in many lands have acted as their own worst enemies by unwittingly adding salt to their soils. The accumulation of salts is perhaps the most vexing problem for long-term human land use in dry regions, but it is only one of several dry-region soil characteristics of that require special attention.

In Chapter 9, we focused on humid regions where soil acidification is unrelenting. In this chapter, we will focus on arid and semiarid regions where most soils are alkaline (have a pH greater than 7). Many of these soils also accumulate detrimental levels of soluble salts (saline soils) or sodium ions (sodic soils), or both. Conditions associated with aridity, alkalinity, salinity, and sodicity can lead to a number of problems in the physical condition and fertility of soils in these regions. Some of these problems will be considered in this chapter, while discussion of others can be found throughout the book. The principles outlined here will help improve your understanding of many concepts dealt with elsewhere in the book: mineral weathering and soil formation (Chapter 2); soil dispersion and crusting (Section 4.6); plant water stress (Section 6.3); infiltration and irrigation (Sections 6.1 and 6.9); plant deficiencies of phosphorus (Section 14.1), zinc, and iron (Section 15.5); and the toxicity of selenium and molybdenum to plants and animals.

For eons, plants and animals native to our deserts and rangelands have adapted to all but the most severe levels of soil alkalinity, salinity, and sodicity. People who wish to inhabit these dry and sunny environments must likewise adapt their actions to these soil conditions. This chapter will provide some of the tools needed to lead the way.

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10.1 CHARACTERISTICS AND PROBLEMS OF DRY REGION SOILS

Soils that characterize low-rainfall regions include most Aridisols, many types of Entisols, and certain suborders (mainly Ustic, Xeric, and Natric) in the orders Mollisols, Inceptisols, Alfisols, and Vertisols (see Sections 3.6-3.13 for a description of these soils). The water-limited, high pH, carbonate-rich nature of dry-region soils results in many characteristics that are not generally found in the acid soils of more humid regions. We will begin by focusing on the nature of alkaline soils that do *not* have excessive levels of salts or sodium, conditions that will be taken up in Sections 10.5–10.7.

Soil Water Supply

About 45% of the earth's land is in arid or semiarid regions where insufficient water generally limits ecosystem productivity. Unlike their counterparts in humid regions, subsoil layers in low-rainfall areas are generally dry, except where the groundwater table is near the surface. Limited moisture in the upper soil horizons and competition for water among plants are principal factors determining the nature and productivity of the native vegetation (see Section 2.4), as well as the capacity of the land to support wild and domesticated animals.

Effective water management is critical for agricultural production on arid- and semiarid-region soils. Irrigation, although extremely important, is practical on only a small fraction of the soils. For nonirrigated (dry land) cultivation, yields of annual crops are severely limited by the scarcity of water for transpiration, so soil management practices that increase water infiltration during periods of rainfall or snowmelt should be encouraged (see Figure 6.9). Likewise, it is often wise to minimize evaporative losses and soil erosion by keeping some vegetative residue cover at or near the soil surface through such practices as stubble mulching or no-till (see Section 6.4). Although some 40% of the world's cultivated land is located there, dry regions are actually dominated by uncultivated deserts and rangelands.

Impacts of Grazing Animals. Grazing animals are essential components of many semiarid rangeland ecosystems. Roaming herds of wild herbivores have evolved special behaviors that help sustain the soil–plant systems they depend on. As a herd passes through a specific area, the intense grazing of the upper portion of vegetation and trampling of the older senescent biomass into the soil promotes the capture of rainfall, the rapid cycling of nutrients (e.g., Section 16.3), and the reseeding and regrowth of palatable plant species—that in turn cover and protect the soil from erosion (Chapter 17). The short duration of each grazing episode and the long rest period afforded the land before grazing is repeated are key features that promote positive impacts. The infrequent occurrence of fast moving fires also commonly plays an important role in maintaining a healthy semiarid ecosystem.

Damaging human interventions include plowing up the soil to remove shrubs, fencing in and poorly managing domesticated animals, and altering the frequency of fires (by suppressing them altogether or setting them too often). Typically a herd of cattle is given continuous access to a certain area of land and the "management" is left to the animals. Such mismanagement can throw the system out of balance, favoring the dominance of scattered unpalatable plants such as woody shrubs with excessive areas of exposed bare ground (Figure 10.1). Under poorly managed continual grazing, trampling by cattle can also negatively impact the ability of the soil to absorb the limited rain that falls on these semiarid lands (Figure 10.2). Such soil degradation can be avoided by systems of intensive cattle management that mimic the behavior of roaming herds (Table 10.1). In such systems, the rancher moves the animals frequently among many small fenced areas called paddocks, exposing the land to intense, but brief periods of grazing followed by long rest period for recovery of the grasses and soil before the herd returns.

Heterogeneity of Soils, Vegetation, and Hydrology of Noncultivated Soils

Seen from the highway, many semiarid landscapes appear to be quite densely covered with vegetation. However, if one walks out into the landscape it is immediately evident that the plants

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Figure 10.1 *Cattle have long replaced wild herbivores in this semiarid rangeland in Chihuahua State, Mexico. The fence separates continuously grazed "ejidos" (areas of communal agricultural land on which individuals farm specific parcels) on the left from rotationally grazed rangeland on the right. Both sides support similar numbers of cattle per hectare. Inset photos (1 m across) show that even during the rainy season flush of growth, the continuously grazed land has about 60% bare soil, very little forage available and high rates of soil erosion.* (Photo courtesy of Ray R. Weil)

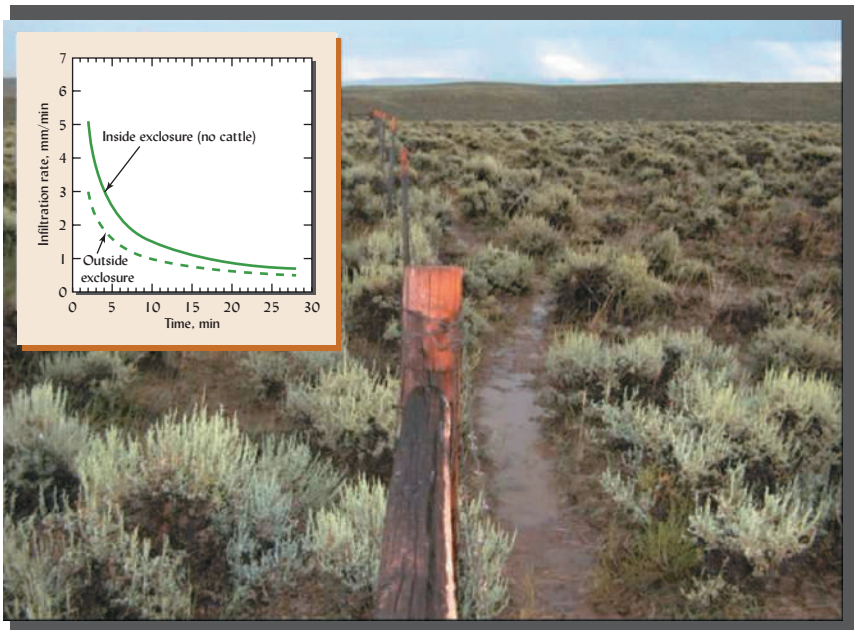

Figure 10.2 *Cattle grazing may reduce water infiltration into semiarid rangeland soils. The effect of cattle is illustrated here by a photo taken immediately after a thundershower and by the mean infiltration measurements presented in the graph. The fence excluded cattle from the area on the left. Note the surface ponding and water running off between the shrubs on the right side where cattle have grazed. The scattered shrubs partially protect the soil under them from trampling by animal hooves, but the dominance of sagebrush shrubs with little grass cover between them is often a sign of poor grazing management.* (Photo courtesy of Sally Madden, University of Wyoming)

are widely spaced, with much of the surface being quite bare of vegetation (Figures 10.2 and 2.28). Such patchy vegetation is characteristic of environments in which water is too sparse to support a complete vegetative cover (see Section 6.4). Less obvious to the casual observer, the soil under the plants is quite different from that in the bare spaces. Because of positive feedback loops, this difference is both a result of—and a cause of—the scattered plant distribution.

Islands of Fertility. Soil scientists studying arid lands have found that plants generally enhance the soil beneath them in several ways. Plants add litter, host macro- and microorganisms, trap windblown particles, and redistribute the limited supplies of water (see Section 6.23). The enrichment of the soil under the vegetation and depletion of the interplant soil is commonly accentuated by the actions of grazing animals that typically congregate and leave their wastes in the shade under the vegetation (Figure 10.3).

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Table 10.1
COMPARATIVE SOIL IMPACTS OF CATTLE GRAZING MANAGEMENT SYSTEMS ON USTOLLS, USTALFS, AND USTERTS IN THE SEMIARID GRASSLANDS OF NORTH TEXAS, USA

The multipaddock system involved crowding cattle in small areas (paddocks) for short periods of time after which they were moved to new area of the ranch while the previous paddocks recovered. This system allowed the land to carry the same number of cattle per ha while causing much less soil degradation than the heavy continuous grazing system in which the herd was given continuous access to the whole ranch. Some 26 sites in nine ranches were compared after a decade or more of management system implementation, taking into account differences in soils and landscape positions.

	Grazing management			
Parameter	**Heavy continuous**	**Light continuous**	**Multipaddock**	**Graze exclosure**
Stocking rate (animal units/100 ha)	27	14	27	0
Hydraulic conductivity ($K \times 10^{-4}$)	44a	53a	60a	66a
Soil compaction (penetration resistance, Joules)	246a	212b	174bc	160c
Runoff water loss (cm h^{-1})	2.0a	0.3b	1.4a	1.8a
Sediment loss (kg ha^{-2})	180a	20b	40b	40b
Soil organic matter (%)	2.4c	3.2b	3.6a	3.6a
Soil ratio of total fungi to total bacteria	1.2b	1.1b	3.1a	0.7b

Data selected from Teague et al. (2011). For each measured parameter (table row) values followed by the same lowercase letter are statistically considered not to differ from each other.

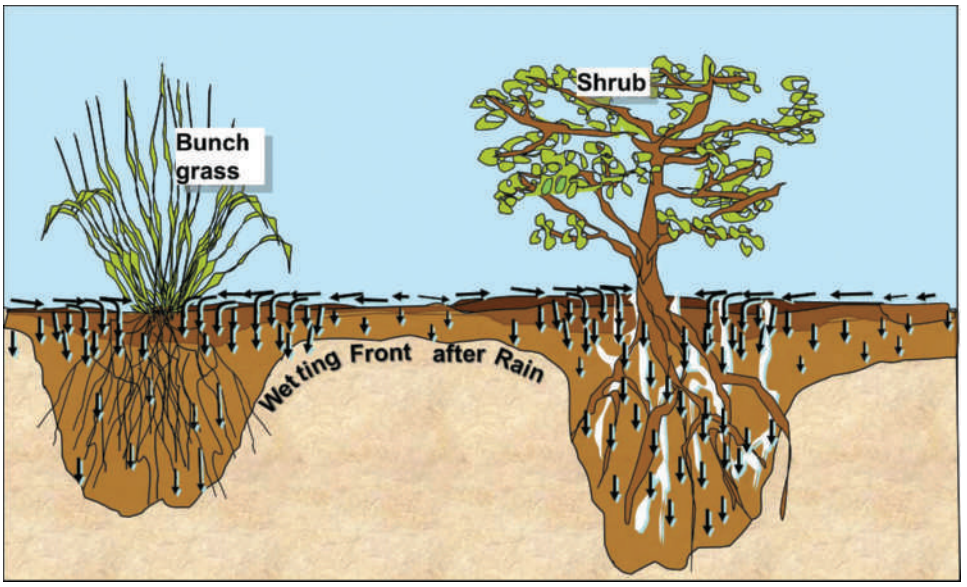

Figure 10.3 *Differential runoff and infiltration rates may give rise to "islands" of enhanced soil water availability in arid and semiarid rangelands. Slight depressions and other features initially concentrate rainwater in small areas. Once plants establish in a pocket of relatively high moisture, they tend to amplify the soil heterogeneity because their litter and roots further enhance water infiltration in their vicinity.* (Diagram courtesy of Ray R. Weil)

Soils under clumps of vegetation therefore become higher in organic matter, silt, and clay, as well as richer in nitrogen and other nutrients. In addition, increased soil organic matter from plant litter leads to greater surface soil aggregation and resistance to slaking and dispersion when wetted by rain (Figure 10.3 graphs and Section 4.5).

Generations of plant roots create a network of biopores open to the surface, and the plant canopy partially protects the surface soil structure when it rains (see Section 17.5). All these effects lead to a notably enhanced infiltration of water and improved soil health in soils of the vegetated patches (Figure 10.4).

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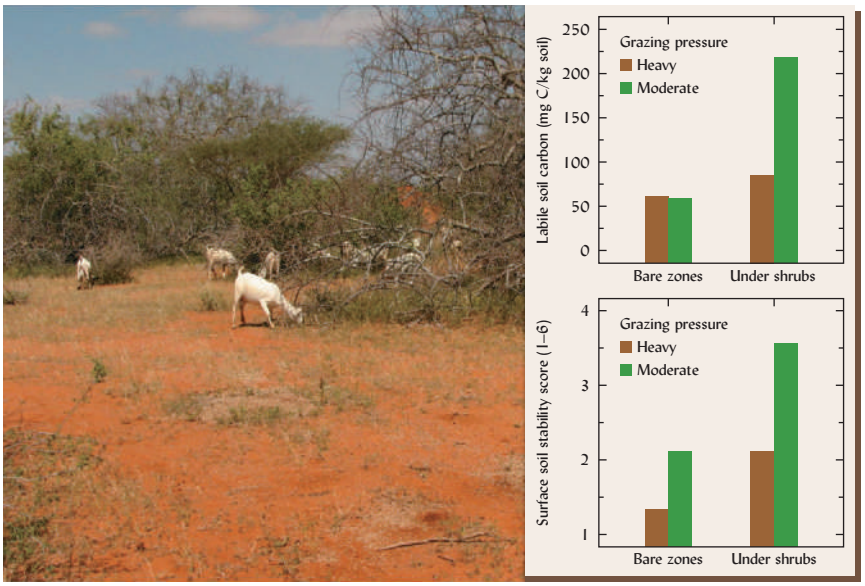

Figure 10.4 *Moderate grazing by livestock such as sheep, goats, cattle, and camels tends to accentuate the heterogeneity and patchiness of vegetation and soils in semiarid rangelands (such as this rangeland in northern Kenya). Under moderate levels of grazing, the soil under shrubs tends to have greater labile organic matter levels (upper right) and greater resistance to slaking and sealing under the impact of rain drops (lower right). Heavy (over-) grazing reduced the level of both soil properties, particularly under the shrubs.* (Data and photo courtesy of Ray R. Weil)

The increased availability of soil moisture and nutrients enhances plant growth, which in turn further promotes the processes just mentioned. Over time, this *positive feedback loop* increases soil productivity in the vegetated patches while soil productivity in the bare unvegetated bare spaces declines. These so-called "islands of fertility" are a common feature of many arid land soils, especially those with sandy texture. Vegetation can also encourage "islands of fertility" by protecting soil from erosive desert winds (see Figure 10.5 for an extreme example). In certain tropical arid lands with long, gentle slopes, these processes lead to 2- to 4-m wide bands of shrub vegetation alternating with bands of bare soil, giving the terrain an appearance termed "tiger stripes" when seen from a distance.

Hydrologic heterogeneity (e.g., differences in infiltration capacity from place to place) may enhance ecosystem productivity and resilience in water-scarce environments. On a scale of centimeters to meters, an uneven soil surface with many small depressions that collect water (such as those caused by large animal hooves) increases the time for infiltration and reduces runoff from that part of the landscape. This natural process has been mimicked to improve rangeland productivity by use of heavy rollers with raised knobs that imprint a pattern of small depressions into the soil surface. In some desert areas, a surface layer of rock fragments plays a critical role in infiltration and runoff processes.

Figure 10.5 *"Islands" of relatively fertile soils commonly form under the influence of perennial vegetation in arid environments. This rather extreme example of the "island of fertility" phenomenon is in the Black Desert of the Sahara in western Egypt. The "islands" of soil preserved under the shrubs are 2–3 m high and 8–10 m in diameter. The intershrub areas are covered by virtually barren, shifting sands.* (Photo courtesy of Ray R. Weil)

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Desert Pavement. A large percentage of desert land (especially in North America) is naturally covered by a thin (usually single) layer of rock fragments ranging in size from coarse gravel to cobbles (see Figure 3.26). When this layer covers at least 65% of the soil surface it is termed *desert pavement*, as it has the appearance of a street carefully paved with cobblestones. The rock fragments protect the soil underneath from wind and water erosion, while trapping windblown particles that add more soil. However, where the rock fragment cover is nearly complete, water entry into the soil may be reduced and runoff increased. In fact, the density of desert pavement can profoundly affect the amount of water available for plant uptake and for such soil formation processes as the leaching of salts. Soils covered with desert pavement may exhibit much higher salt contents in the upper horizons than do adjacent soils without desert paving (Figure 10.6). These effects on water and salt in the soil, in turn, influence the distribution of desert shrubs in the landscape; more shrubs tend to grow where the desert pavement is less complete or absent.

Concentrating water in localized areas of enhanced infiltration assures that at least some parts of the landscape receive enough water for plant survival and productivity. Those parts of the landscape that experience low infiltration and high runoff rates serve as *water sources*. In other parts of the landscape, soils exhibit high infiltration rates and low runoff and serve as *water sinks*. On a landscape scale, topography plays an especially important role in the hydrology of arid lands. Steep slopes, especially when barren of vegetation, tend to absorb little water during heavy rainstorms and generate large volumes of runoff that moisten downslope soils. Ancient peoples learned to harness these landscape-scale processes to allow agricultural production in regions where direct rainfall is far too low to sustain crops or orchards (Box 10.1).

Microbiotic Crusts. In their natural state, fine-textured arid region soils commonly exhibit a thick, dark-colored, sometimes jagged, coating or crust on the soil surface. These crusts are actually fragile living structures. We will discuss them in detail in Section 11.14, but they deserve mention here because of their role in the hydrology of many desert areas. Formed by algae, fungi, and cyanobacteria, **microbiotic crusts** originally covered much of the intershrub surface on undisturbed, fine-textured alkaline soils not covered by rock fragments. However, in many places, traffic by humans and cattle has degraded most of the

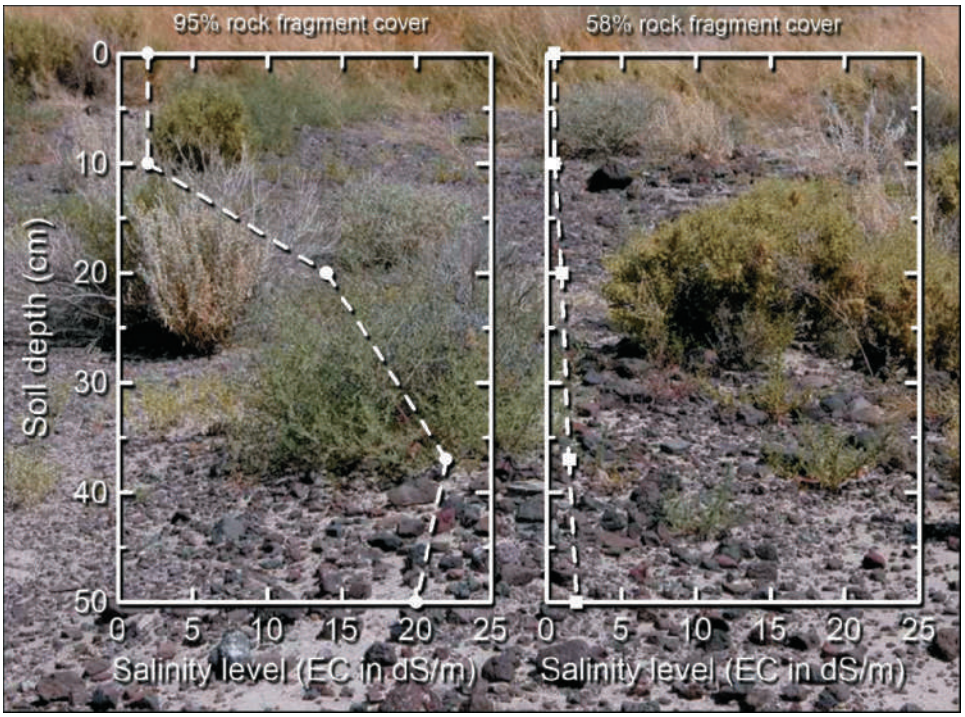

Figure 10.6 *Soils with only scattered rock fragments (generally less than two-thirds cover) have relatively high rates of water infiltration and therefore are largely leached of salts in the upper layers (*right graph for 58% rock cover*). Where the rock fragment cover is more complete, it is termed* desert pavement. *Like the pavement on a parking lot, desert pavement greatly reduces water infiltration; hence salts are not leached very deeply in the soil (*left graph for 95% rock cover*). In the photograph rock fragment cover varies from nearly 90% to less than 50%.* [Data for sites in the Mojave Desert from Wood et al. (2005); photo courtesy of Ray R. Weil]

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BOX 10.1

RUNOFF FARMING: PEOPLE USING DESERT SOILS[a]

Several thousand years ago, two completely independent civilizations learned to manipulate landscape hydrology to allow farming in their respective desert habitats, the Nabateans in the Negev Desert and the Anasazi Indians in the deserts of the American Southwest. These people constructed diversions to collect runoff water from large areas of low-infiltration, sloping land (typically 20–100 ha) and concentrate this water on small, cultivated areas in the valley bottoms (typically about 1 or 2 ha). To enhance the performance of their *runoff farms*, they terraced and built berms around their valley bottom fields to maximize the infiltration and storage of water there. On the sloping catchment land their aim was to maximize the runoff. This they did by removing surface rocks and debris that normally slow down runoff and increase infiltration. These practices may have supplied their cultivated fields with 5–6 times the amount of water that would normally have fallen directly on these fields as rain. The ruins of their farms and water collection systems can still be seen in parts of southern Israel and Arizona, USA (Figure 10.7, *left*). Similar water harvesting techniques are currently being introduced in semiarid places where climate change has reduced already marginal rainfall amounts so that in most years the rain falling directly on an area of cropland is no longer sufficient to grow even a modest crop (Figure 10.7, *right*).

Figure 10.7 *Runoff farming, old and new.* (Left) *Rows of fruit trees and vines can grow in this extremely arid landscape only because the small area catchment area devoted to their cultivation receives runoff water from the surrounding barren during the few rainstorm that occur. This scientific experiment in the Negev desert of southern Israel reconstructs the runoff farming techniques of the ancient Nabetean people.* (Right) *A modern project to introduce runoff farming in a dry area of northern Tanzania. During the short rainy season most of the rain falls on the high mountains in the distance, resulting in torrents of runoff water surging across the plain in the foreground. A network of trenches was made to guide this water to crop fields and to underground storage tanks. The tank in the foreground is covered with a metal roof to reduce evaporation losses and will provide water for irrigation after the rainy season is over.* (Left photo courtesy of R. Gilker; right photo courtesy of Ray R. Weil)

[a]Norton et al. (2007) discuss hydrologic and fertility aspects of present-day runoff farming in New Mexico.

original crust (Figure 10.8). While all forms of microbiotic crusts dramatically reduce soil erosion by wind and water (Section 17.11), the rough or pinnacled types also increase water infiltration rates. The smooth-surfaced types may have the opposite effect.

Calcium-Rich Layers

Soils of low-rainfall areas commonly accumulate calcium carbonate that forms a *calcic horizon* at some depth in the soil profile (Figures 10.9 and 3.26). Calcareous soil materials (those with free calcium carbonates) can be distinguished in the field by the effervescence (fizzing) that occurs if a drop of acid (10% HCl or strong vinegar) is applied. The high carbonate concentrations in calcic horizons can inhibit root growth for some plants. In eroded spots, or in regions of very low rainfall (<25 mm/yr), carbonate concentrations may be found at or near the soil surface (Figure 10.10). In these cases, serious micronutrient and

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Figure 10.8 *The sparse vegetation and exposed soil surface of a degraded rangeland in Arizona, USA. Only a few scattered fragments remain of the biological crust* (see Section 11.14) *that once covered the soil between clumps of vegetation. Much of the soil is now bare and its degraded structure seals the surface, reducing its capacity to absorb water from the infrequent but high-intensity rainstorms that occur in this region. Ecosystems in arid and semiarid regions are often quite sensitive to such disturbances as overgrazing and off-road vehicle traffic. Partly because of the precarious water balance in these systems, recovery of rangeland vegetation may be very slow. Knife handle is 12 cm long.* (Photo courtesy of Ray R. Weil)

Figure 10.9 *Calcium carbonate accumulation in the lower part of the B horizon (Btk) and the upper part of the C horizon (the knife is inserted at the upper boundary of the Ck horizon) characterizes this Ustoll and many other soils of arid and semiarid regions. Such calcareous layers maintain high pH and calcium levels, constraining the availability of nutrients such as phosphorus, iron, manganese, and zinc. Knife handle is 12 cm long.* (Photo courtesy of Ray R. Weil)

phosphorus deficiencies can be induced in plants that are not adapted to calcareous conditions (see following).

In other alkaline soils, one or more subsoil layers may be cemented into hard, concrete-like horizons such as petrocalcic layers or duripans (Figure 3.26). Many alkaline soils also contain layers rich in calcium sulfate (gypsum), a mineral much more soluble than calcium carbonate. The depth of calcic horizons and gypsic horizons is largely determined by the age of the soil and by the amount of rainfall available to leach these minerals downward.

Colloidal Properties

Cation Exchange Capacity (CEC). The CECs of alkaline soils are commonly higher than those of acid soils with comparable soil textures. This is true for two reasons. First, the 2:1-type clays that are most common in alkaline soils possess high amounts of permanent charge. Second, the high pH levels of alkaline soils stimulate high levels of pH-dependent charges on the soil colloids, especially humus (Section 8.9).

Clay Dispersion. Clays in alkaline soils are particularly subject to deflocculation or dispersion because: (1) the iron and aluminum coatings that act as strong flocculating and cementing

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Figure 10.10 *Eroded Mollisol hilltop (foreground) with whitish calcareous horizon exposed at the surface and resulting in severely iron deficient sorghum.* (Photo courtesy of Ray R. Weil)

agents in acid soils are largely lacking in alkaline soils, (2) the types of clays dominant in alkaline soils (Section 8.5) are especially susceptible to dispersion, and (3) monovalent ions (Na^+ and K^+) that are easily leached from acid soils (see Section 8.10) largely remain unleached in the soils of dry regions. Dispersion of soil clay leads to drastically reduced macroporosity, aeration, water percolation, and to the sealing of the soil surface (see Sections 10.5–10.6).

Nutrient Problems

The availability of most nutrient elements is markedly influenced by soil pH (see Figure 9.22), so alkaline soils can be expected to exhibit special problems regarding the solubility of plant nutrients and other elements. In addition, the minimal weathering that takes place in dry regions allows many weatherable and relatively soluble minerals to remain in the soil, in some cases contributing high levels of certain elements to the soil–plant–animal system.

Micronutrient Metals. The micronutrients zinc, copper, iron, and manganese are readily available in acid soils, but are much less soluble at pH levels above 7 (see Section 15.8). Therefore, in alkaline soils plant growth is commonly limited by deficiencies of these elements, deficiencies of iron and zinc being especially common in irrigated tree crops, as well as in dryland wheat and sorghum (Figure 10.10). The low organic-matter levels of most dry-region soils further reduce the availability of these metals.

These deficiencies can be especially acute when alkaline soils are brought under irrigation. Because of adverse reactions in alkaline soils, correction of these problems often requires special protective organic complexes called **chelates** (see Section 15.9) and the direct application of these micronutrients to plant foliage via foliar sprays or irrigation water.

Micronutrient deficiencies in alkaline soils can be especially troublesome for ornamental plantings (Figure 10.11) when using species native to humid regions. Ornamental landscape managers should select plants that are adapted to alkaline soil—or micronutrient deficiencies are likely to occur.

Boron and Molybdenum. Boron deficiency is common at high pH levels in both sandy soils (because of low boron content) and clayey soils (because the boron is tightly held by the clay). In addition, plants tend to have a higher requirement for boron if calcium is abundant. For all these reasons, boron deficiencies are quite common in alkaline soils (see Section 15.11). On the other hand, since arid region soils do not lose boron by leaching as humid region soils do, boron toxicity is also a problem, especially where irrigation water containing boron is used.

Molybdenum. In contrast to boron, molybdenum availability is high under alkaline conditions—so high that in some areas molybdenum toxicity is a problem in the form of disease known as **molybdenosis** (see Section 15.11).

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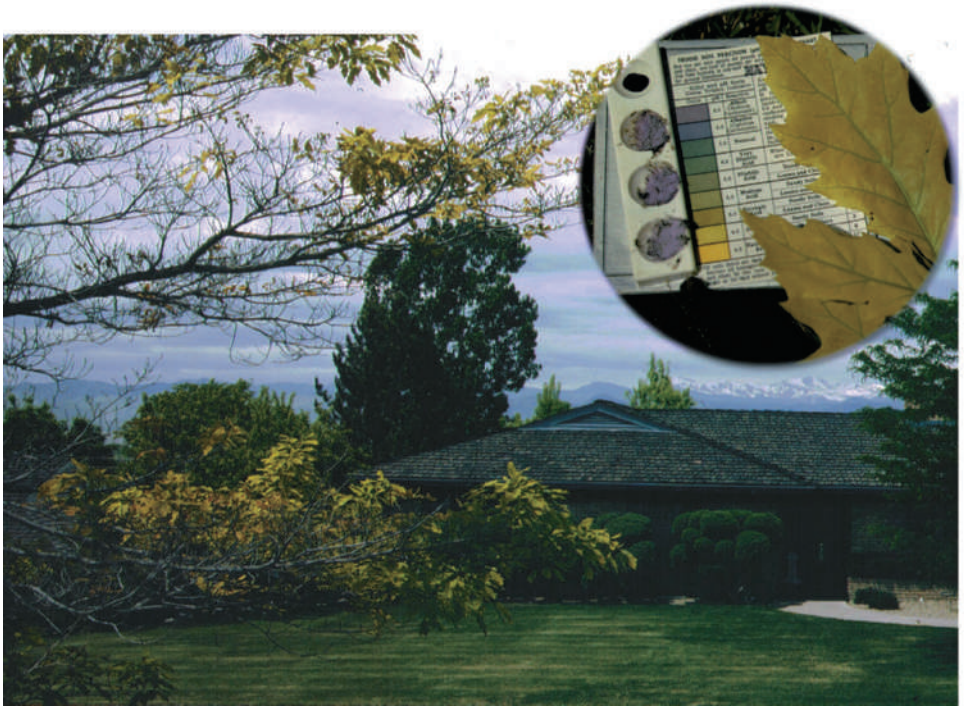

Figure 10.11 *Ornamental oak trees that thrive in acid soils suffer from deficiencies of iron and other micronutrients when grown on alkaline soils, as in the Denver in Colorado, USA, suburb shown. Pale-colored foliage (chlorosis) and dying branches of the tree in the foreground are symptoms of iron or manganese deficiency. (Inset) Chlorotic leaf with green veins and indicator dye showing pH 8. Remedies could include: (1) selecting a species better adapted to alkaline soils, (2) acidifying the soil around the tree, or (3) Applying micronutrients to the soil in chelated form or or to the foliage in a spray.* (Photo courtesy of Ray R. Weil)

Phosphorus. Deficiency of the macronutrient phosphorus (P) is a widespread problem in arid regions because the abundant Ca^{2+} and Mg^{2+} ions dissolved in alkaline soils act as common ions, which constrain the dissolution of phosphorus-carrying minerals. Even P added as soluble fertilizer soon reacts with the abundant Ca^{2+} in solution to form calcium-phosphate compounds that become increasingly insoluble over time (see Sections 14.5–14.9 for more detail on P availability).

In light of the many impacts of high pH just discussed, we now turn our attention to why the pH in dry region soils is almost always alkaline.

10.2 CAUSES OF HIGH SOIL pH (ALKALINITY)

In regions where precipitation is less than potential evapotranspiration (see Section 6.3 and Figure 6.26), the cations released by mineral weathering accumulate because there is not enough rain to thoroughly leach them away. The pH of soils in these arid and semiarid environments is generally in the alkaline range—that is, 7 or above.

There seems to be considerable confusion about the terms **alkaline** and **alkalinity**, and people often use these terms *wrongly* to describe soils characterized by detrimental levels of soluble salts or sodium. Alkaline soils are simply those with a pH above 7.0. *Alkalinity* refers to the concentration of OH^- ions, much as *acidity* refers to that of H^+ ions. *Alkaline* soils should not be confused with *alkali* soils.[1] The latter name is an obsolete term for what are now called **sodic** or **saline–sodic** soils, those with levels of sodium high enough to be detrimental to plant growth (see Section 10.5). Current classification of salt-affected soils includes consideration of both pH and salinity measures.

Sources of Alkalinity

Minimal leaching in dry environments means that soil acidification is minimized. The cations in the soil solution and on the exchange complex are mainly Ca^{2+}, Mg^{2+}, K^+, and Na^+. As explained in Section 9.1, these cations are nonhydrolyzing and so do not produce acid (H^+) upon

[1]The terms *alkali* and *alkaline* are derived from the chemical grouping of elements into the monovalent alkali earth metals (lithium, sodium, potassium, rubidium, and cesium) and the divalent alkaline earth metals (beryllium, magnesium, calcium, strontium, and barium). See the periodic table in Appendix B.

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reacting with water as Al^{3+} or Fe^{3+} do. However, they generally do not produce OH^- ions either. Rather, their effect in water is neutral,[2] and soils dominated by them have a pH about 7 unless certain *anions* are present in the soil solution. The basic hydroxyl (OH^-)-generating anions are principally **carbonate** (CO_3^{2-}) and **bicarbonate** (HCO_3^-). These anions originate from the dissolution of such minerals as calcite ($CaCO_3$) or from the dissociation of carbonic acid (H_2CO_3)

$$\underset{\text{Calcite (solid)}}{CaCO_3} \rightleftharpoons \underset{\text{(dissolved in water)}}{Ca^{2+}} + \underset{\text{(dissolved in water)}}{CO_3^{2-}} \tag{10.1}$$

$$CO_3^{2-} + H_2O \rightleftharpoons HCO_3^- + OH^- \tag{10.2}$$

$$HCO_3^- + H_2O \rightleftharpoons H_2CO_3 + OH^- \tag{10.3}$$

$$\underset{\text{Carbonic acid}}{H_2CO_3} \rightleftharpoons H_2O + \underset{\text{(gas)}}{CO_2\uparrow} \tag{10.4}$$

In this series of linked equilibrium reactions, carbonate and bicarbonate act as bases because they react with water to form hydroxyl ions and thus raise the pH. The relationships among the concentrations of these ions and that of the H^+ ion (expressed as pH) are illustrated in Figure 10.12. The importance of these reactions in **soil buffering** (resistance to pH change) is discussed in Section 9.4.

Influence of Carbon Dioxide and Carbonates

The direction of the overall reaction (Reactions (10.1)–(10.4) determines whether OH^- ions are consumed (proceeding to the left) or produced (proceeding to the right). The reaction is controlled mainly by the precipitation or dissolution of calcite on the one end and by the

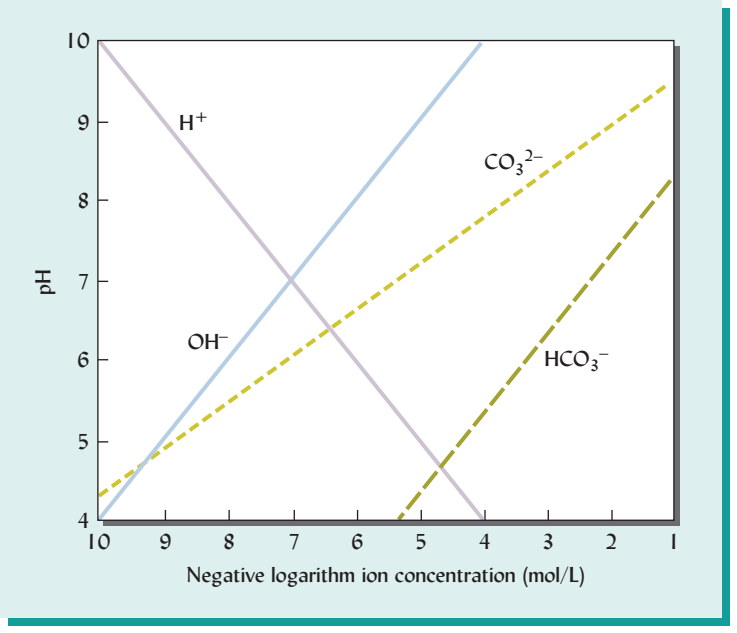

Figure 10.12 *Effect of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) on the concentrations of H^+ and OH^- ions in aqueous solution, expressed as negative logarithms. The H^+ line represents an increase in pH (−log H^+ ions) from 4 to 10. Note that as the concentrations of CO_3^{2-} and HCO_3^- go up (to the right), so does the concentration of OH^-. Since the H^+ ion concentration is inversely related to the OH^- concentration, the pH also rises.*

[2]The cations Ca^{2+}, Mg^{2+}, K^+, Na^+, and NH_4^+ have been traditionally called *base* or *base-forming* cations as a convenient way of distinguishing them from the acid cation, H^+, and the H^+-forming cation Al^{3+}. However, since Ca^{2+} and associated cations do not accept protons, they are technically not bases. Consequently, it is less misleading to refer simply to acid cations (H^+, Al^{3+}) and nonacid cations (most other cations). Likewise, the term *nonacid saturation* should be used rather than *base saturation* to refer to the percentage of the exchange capacity satisfied by nonacid cations (usually Ca^{2+}, Mg^{2+}, K^+, and Na^+) on the exchange complex (see also Section 9.3).

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production (by respiration) or loss (by volatilization to the atmosphere) of carbon dioxide at the other end. The concentration of CO_2 in the atmosphere is about 0.0035%, but may be as high as 0.5% in soil air due to respiration by roots and microorganisms (see Section 7.2). Therefore, biological activity in soils tends to lower the pH by driving the reaction series to the left.

The other process that limits the rise in pH is the precipitation of $CaCO_3$ that occurs when the soil solution becomes saturated with respect to Ca^{2+} ions. Such precipitation removes Ca from the solution, again driving the reaction series to the left (lowering pH). Because of the limited solubility of $CaCO_3$, the pH of the solution cannot rise above 8.4 when the CO_2 in solution is in equilibrium with that in the atmosphere. The pH at which $CaCO_3$ precipitates in soil is typically only about 7.0–8.0, depending on how much the CO_2 concentration is enhanced by biological activity. This is an important point to remember because it suggests that if other carbonate minerals more soluble than $CaCO_3$ (e.g., Na_2CO_3) were present, the pH would rise considerably higher (see Section 10.4). Indeed this is the case; **calcareous** (calcite-laden) soil horizons range in pH from 7 to 8.4 (tolerable by most plants), while sodic (sodium carbonate–laden) horizons may range in pH from 8.5 to as high as 10.5 (levels toxic to many plants).

Role of the Cations (Na^+ Versus Ca^{2+})

As just suggested, the particular cation associated with carbonate and bicarbonate anions influences the pH level attained. Calcium and sodium are the principal cations involved (although magnesium or others can play a role, as well). If Na^+ is prominent on the exchange complex and in the soil solution, the set of reactions just described (Reactions (10.1)–(10.4) will still apply, except that the first step (Reaction (10.1) will be replaced by the following:

$$\underset{\text{(solid)}}{Na_2CO_3} \rightleftharpoons \underset{\text{(dissolved in water)}}{2Na^+} + \underset{\text{(dissolved in water)}}{CO_3^{2-}} \qquad (10.5)$$

Because sodium carbonate (and sodium bicarbonate) is much more water-soluble than calcium carbonate, the set of reactions will proceed more readily to the right, producing more hydroxyl ions and thus a higher pH. With high concentrations of CO_3^{2-} ions in solution, the pH can rise to 10 or higher (see Figure 10.12). It is fortunate for plants that Ca^{2+}, not Na^+, ions are dominant in most soils.

Influence of Soluble Salt Level

The presence in the soil solution of high levels of neutral salts (from sources other than carbonates, such as $CaSO_4$, Na_2SO_4, NaCl, and $CaCl_2$) tends to lower the pH by moderating the alkalinizing reactions just discussed. Increasing the concentration of Ca^{2+} or Na^+ ions on the right side of Reaction (10.1) or (10.5) drives the reaction to the left by *the common ion effect.* The *common ion effect* is a shift in equilibrium that occurs because of the addition of an ion already involved in an equilibrium reaction. In this example, Ca^{2+} or Na^+ added from sources other than $CaCO_3$ or Na_2CO_3 will reduce the dissolution of these carbonates. With less $CaCO_3$ or Na_2CO_3 going into solution, fewer CO_3^{2-} and HCO_3^- ions are formed, and the pH does not rise as high as it would have if less salt were present.

Nonetheless, salt accumulation is one of the most troubling problems of dry region soils. Hence, we will now turn our attention to the characteristics and management of salt-affected soils.

10.3 DEVELOPMENT OF SALT-AFFECTED SOILS[3]

Salt-affected soils are widely distributed throughout the world (Figure 10.13), typically in areas with precipitation-to-evaporation ratios of 0.75 or less and in low, flat areas with high water tables that may be subject to seepage from higher elevations (Figure 10.14). Salt-affected soils cover approximately 7% of the Earth's total land area, about 23% of its cultivated agricultural land, and almost 50% of its irrigated land. In the western United States nearly

[3]For a discussion of these soils, which are also referred to as *halomorphic soils*, see Abrol et al. (1988), Szabolcs (1989), Rengasamy (2006) and Wichelns and Qadir (2015).

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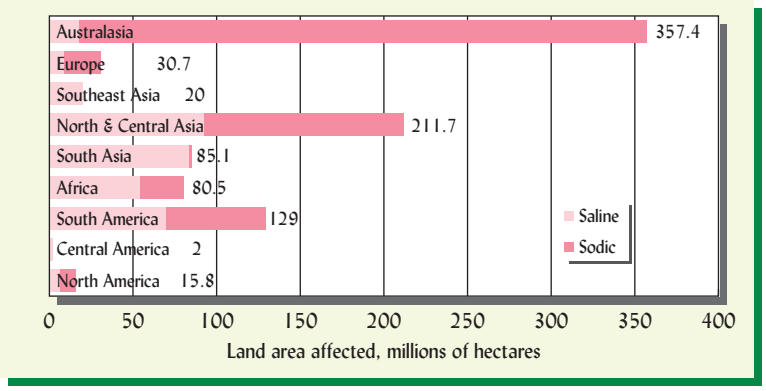

Figure 10.13 *Area extent of salt-affected soils (saline or sodic) in different regions of the world. In total, some 933 million hectares are affected by salt globally, 352 million are saline and 581 million are sodic. The numbers represent the sum of saline and sodic lands.* [Graphed from tabular data in Szabolcs (1989) as cited in Rengasamy (2006)]

Figure 10.14 *Salt-encrusted land near the Great Salt Lake in Utah, USA. Looking almost like snow, the salt crust forms when groundwater rises by capillarity and evaporates from the soil surface, leaving behind the salts that had been dissolved in the water.* (Photo courtesy of Ray R. Weil)

16 million ha of cropland and pasture are currently affected by salinity. In some regions the area of land so affected is growing by about 10% annually.

In most cases, the soluble salts in soils originate from the weathering of primary minerals in rocks and parent materials. In extremely dry regions (annual precipitation), calcium sulfate accumulations (gypsic horizons) may form near the soil surface where this relatively soluble mineral may create a saline condition. However, in most cases, salts are transported to a developing salt-affected soil as ions dissolved in water. The salt-containing water moves through a landscape from areas of higher to lower elevations and from soil zones that are wetter to those that are drier. The water is eventually lost by evaporation. However, the dissolved salts cannot evaporate, and therefore they are left behind to accumulate in the soil. This is true in both irrigated and nonirrigated landscapes.

Many soils become salt-affected because changes in the local water balance, usually brought about by human activities, increase the input of salt-bearing water more than they increase the output of drainage water. Increased evaporation, waterlogging, and rising water tables usually result. It is worth remembering the irony that *salts usually become a problem when too much water is supplied, not too little*.

Accumulation of Salts in Nonirrigated Soils

Large areas of soils in arid and semiarid regions are affected by some degree of salinity. The salts are primarily chlorides and sulfates of calcium, magnesium, sodium, and potassium. These salts accumulate naturally in some surface soils because there is insufficient rainfall to flush them from the upper soil layers. In coastal areas, sea spray and inundation with seawater can be locally important sources of salt in soils.

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Other localized but important sources are fossil deposits of salts laid down during geological time in the bottom of now-extinct lakes or oceans or in underground saline water pools. These fossil salts can be dissolved in groundwater that moves horizontally over underlying impervious geological layers and ultimately rises to the surface of the soil in the low-lying parts of the landscape. The salts then concentrate near or on the surface of the soil in these low-lying areas, creating a saline soil. The low-lying areas where the saline groundwater emerges are termed **saline seeps**.

Saline seeps occur naturally in some locations, but their formation may be greatly increased when the water balance in a semiarid landscape is disturbed by bringing land under cultivation (Figure 10.15). Replacement of native, deep-rooted perennial vegetation with annual crop species greatly reduces the annual evapotranspiration, especially if the cropping system includes periods of fallow during which the soil is bare of vegetation. The decreased evapotranspiration allows more rainwater to percolate through the soil, thus raising the water table and increasing the flow of groundwater to lower elevations. In dry regions, soils and substrata may contain substantial amounts of soluble salts that can be picked up by the percolating water. If a shallow layer restricts percolation, it will further encourage the flow of the salt-laden groundwater across the landscape toward the lowest elevations. Eventually, the water table may come to within 1 m or less of the soil surface, and capillary rise will begin to contribute a continuous stream of salt-laden water to replace the water lost at the surface by evaporation. The evaporating water will leave behind the salts, which soon will accumulate to levels that inhibit plant growth. Year by year the evaporation zone will creep up the slope, and the barren area will become larger and more saline. Millions of hectares of land in Australia, North and South America, and other semiarid regions have been degraded in this fashion.

The exchange complex of most salt-affected soils is dominated by Ca^{2+} and Mg^{2+} ions, with little exchangeable Na^{+}. However, where groundwater or irrigation water carries a significant proportion of Na^{+} ions, and especially if HCO_3^{-} ions are present, Na^{+} ions may come to saturate a major part of the colloidal exchange sites leading to deterioration of soil aggregates and greatly reduced soil permeability. If the Na^{+} saturation exceeds 15%, the term ***sodic soil*** applies, signaling extremely adverse conditions (see Sections 10.5 and 10.6).

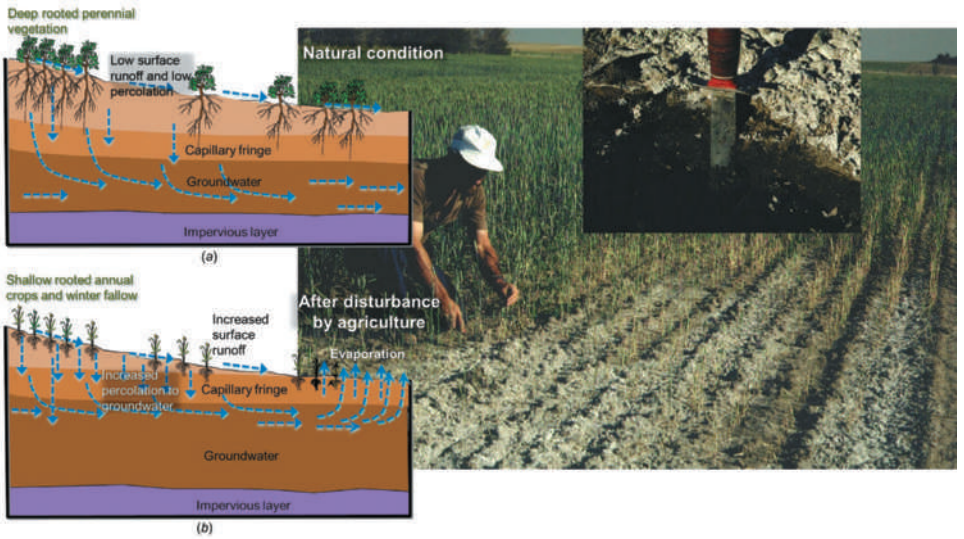

Figure 10.15 *Saline seep formation in a semiarid area where the salt-rich substrata are underlain by an impermeable layer. (a) Under deep-rooted perennial vegetation, transpiration is high and the water table is kept low. (b) After conversion to agriculture, shallow-rooted annual crops take up much less water, especially if fallow is practiced, allowing more water to percolate through the salt-bearing substrata. Consequently, in lower-elevation landscape positions, the wet-season water table rises close to the soil surface. This allows the salt-laden groundwater to rise by capillary flow to the surface, from which it evaporates, leaving behind an increasing accumulation of salts. Note that the diagrams greatly exaggerate vertical distances. (c) A spreading saline seep area in eastern Montana, USA, where wheat fallow cropping has replaced natural deep-rooted prairie vegetation. (d) Close-up of salt crust over moist soil.* (Photos and drawings courtesy of Ray R. Weil)

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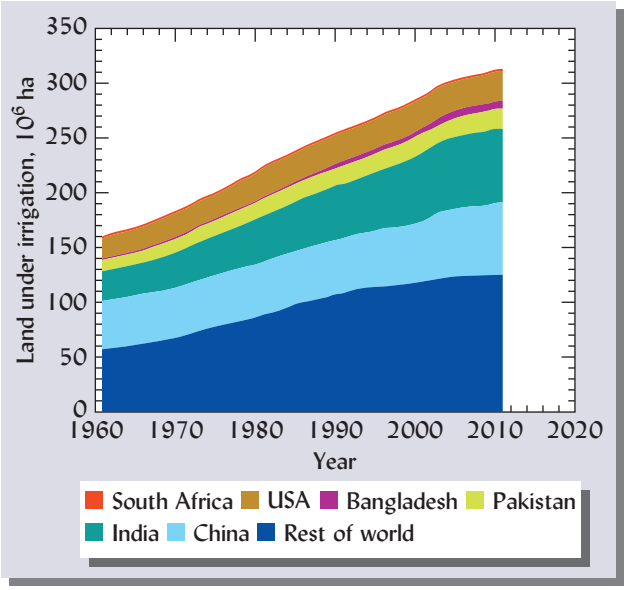
Irrigation-Induced Salinity and Alkalinity

Irrigation not only alters the water balance by bringing in more water, it also brings in more salts. Whether taken from a river or pumped from the groundwater, even the best quality freshwater contains some dissolved salts (see Section 10.8). The amount of salt brought in with the water may seem negligible, but the amounts of water applied over the course of time are huge. Again, pure water is lost by evaporation, but the salt stays behind and accumulates (Figure 10.16). The effect is accentuated in arid regions for two reasons: (1) the water available from rivers or from groundwater is relatively high in salts because it has flowed through dry-region soils that typically contain large amounts of easily weatherable minerals, and (2) the dry climate creates a relatively high evaporative demand, so large amounts of water are needed for irrigation. An arid-region farmer may need to apply 90 cm of water to grow an annual crop. Even if this is good-quality water relatively low in salts, it will likely dump more than 6 Mg/ha (3 tons/acre) of salt on the land every year (see Section 10.8).

During the past half century, people have greatly expanded the area of land under irrigation in order to produce the food needed by their rapidly growing human populations (Figure 10.17). Consequently, the proportion of arable land that is irrigated has increased dramatically, reaching about 45% in China, 35% in India, 94% in Pakistan, and 24% in

Figure 10.16 *Salinization, the accumulation of soluble salts in soils, can be observed in the potting medium of houseplants (left) and in irrigated fields (middle and right). The salt accumulates because of evaporative water loss from soil that is repeatedly supplied with water that contains dissolved salts, even if in low concentrations. Only pure water evaporates; the salts dissolved in the water do not. Note that the salt tends to concentrate at the highest points of the soil surface, from which evaporation loss is greatest and to which the soil solution flows by capillary action.* (Photos courtesy of Ray R. Weil)

Figure 10.17 *The world's land under irrigation has nearly doubled during the past half century, with most of the increases in south Asian countries. It is thought that nearly half of this land is affected by salts.* [Data from FAO (2013)]



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Indonesia. Initially, the expanded irrigation stimulated phenomenal increases in food-crop production. Unfortunately, many irrigation projects failed to provide for adequate drainage. As a result, the process of ***salinization*** accelerated, and in some areas, sodic soils have been created.

These events remind the world of the flat lands of southeastern Iraq where, in biblical times, irrigation water supplied by the Euphrates and Tigris, produced such high crop productivity that the overall region was called the Fertile Crescent. Unfortunately, salinization eventually set in because many of the soils were not naturally well drained and the societies sometimes failed to maintain what artificial drains were created. Salts eventually accumulated to such a degree that crop production declined and the area had to be abandoned. Much of the land has been barren since the twelfth century. Today, societies around the world are repeating the mistakes of the past. Some observers believe that each year, the area of previously irrigated land degraded by severe salinization is greater than the area of land newly brought under irrigation. Truly, the world needs to give serious attention to the large-scale problems associated with salt-affected soils.

10.4 MEASURING SALINITY AND SODICITY

Salt-affected soils adversely affect plants because of the total concentration of salts (*salinity*) in the soil solution and because of relative concentrations of specific ions, especially sodium (*sodicity*).

Salinity[4]

Total Dissolved Solids (TDS). In concept, the simplest way to determine the total amount of dissolved salt in a sample of water is to heat the solution in a container until all of the water has evaporated and only a dry residue remains. A temperature of 180 °C is used to ensure that water of hydration is removed from the salt residue. The residue can then be weighed and the TDS expressed as milligrams of solid residue per liter of water evaporated (mg/L).[5] In water to be used for irrigation, TDS typically ranges from about 5 to 1000 mg/L, while in the solution extracted from a soil sample, TDS may range from about <500 to >10,000 mg/L. As a practical matter, TDS is rarely measured by actual evaporation; rather the **electrical conductivity** (EC) of water or a soil–water mixture is measured and the salinity so measured is expressed either directly in units of conductivity or sometimes used to estimate mg/L TDS.

Electrical Conductivity. Pure water is a poor conductor of electricity, but conductivity increases as more and more salt is dissolved in the water. Thus, the EC of the soil solution gives us an indirect measurement of the salt content. The EC can be measured both on samples of soil mixed with water or on the bulk soil in situ (Table 10.2). It is expressed in terms of deciSiemens per meter (dS/m).[6]

The **saturation paste extract** method is the most commonly used lab procedure and the standard to which the others are usually compared. A soil sample is saturated with distilled water and mixed to the consistency of a paste that glistens with water and flows slightly if jarred. After standing overnight to thoroughly dissolve the salts, the solution is extracted by suction filtration and its electrical conductivity is measured (EC_e). A variant of this method involves measuring the EC of the solution extracted from a 1:2 soil–water mixture after 0.5 h of shaking (EC_w). The latter method takes less time but often is not as well related to the soil solution as is the saturation paste extract method. Values for EC_w can be converted to total dissolved solids if the type of salt is known (see footnote, Table 10.2).

Two more rapid methods that are well correlated to the salinity of the soil solution are: (1) the conductivity of the saturated soil paste itself (EC_p) and (2) the conductivity of a 1:2 soil:water mixture (EC_s). Because the tedious extraction and filtration steps are eliminated, EC_p and EC_s can easily be determined on samples in the field (Figure 10.18).

[4]For an informative discussion of these methods, see Rhoades et al. (1999).

[5]In this case the unit mg/L has the same meaning as parts per million (ppm), since there are a million mg in a kg of water (which has the volume of 1 L). Although ppm is often used in commercial literature, it is an ambiguous expression and should be avoided.

[6]Formerly expressed as millimhos per centimeter (mmho/cm). Since 1 S = 1mho, 1 ds/m = 1 mmho/cm.

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Table 10.2
DIFFERENT MEASUREMENTS FOR ESTIMATING SOIL SALINITY
The methods are well correlated, so each can be converted to any other. The EC_e is the most common standard for comparison.

Measured on a soil sample	
EC_e	Conductivity of the solution extracted from a water-saturated soil paste
EC_p	Conductivity of the water-saturated soil paste itself
EC_w	Conductivity of the solution extracted from a soil–water mixture (usually either 1:2 or 1:5)
EC_s	Conductivity of a 1:1, 1:2, or 1:5 soil–water mixture itself
TDS	Total dissolved solids in water or the solution extracted from a water-saturated soil paste[a]
Measured on bulk soil in place	
EC_a	Apparent conductivity of bulk soil sensed by metal electrodes in soil
EC^*_a	Electromagnetic induction of an electric current using surface transmitter and receiving coils

[a]Note that TDS (mg/L) can be converted to EC_w using these relationships between 0 and 5 dS/m: for Na salts, TDS = 640 × EC_w based on a 1:2 soil:water mixture; for Ca salts, TDS = 800 × EC_w. The dilution effect of varying soil:water ratios must be taken into account when comparing data by the various EC_s and EC_w methods.

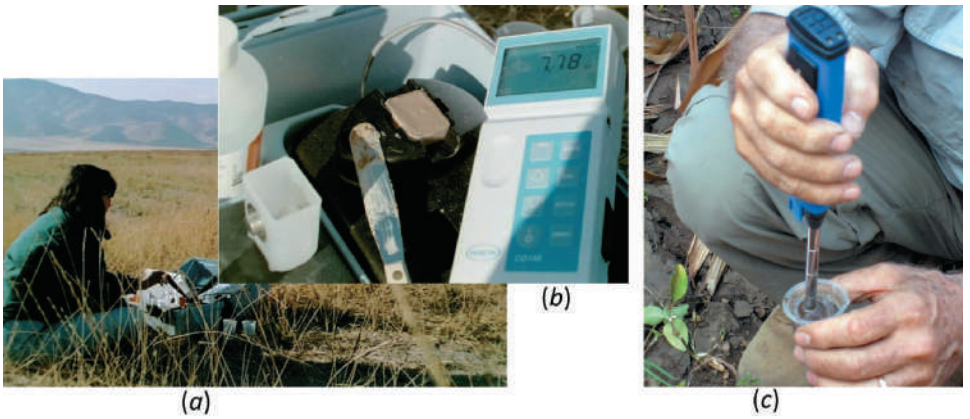

Figure 10.18 *Field determination of soil salinity by electrical conductivity (EC) measurement .* (a) *Soil is stirred with pure water until a saturated paste is made.* (b) *The paste is transferred into a conductivity cup with a flat, circular electrode on either side (inset). This cup is then inserted into a stand that connects the electrodes to a conductivity meter. Note readout of 7.78 dS/m, a level of ECp indicating a highly saline soil that would inhibit the growth of many crops.* (c) *A different direct-read EC instrument is used to measure the ECs of a suspension made by mixing two parts water with one part soil in a small plastic beaker.* (Photos courtesy of Ray R. Weil)

Mapping EC in the Field. Advances in instrumentation now allow rapid, continuous field measurement of bulk soil conductivity, which, in turn, is directly related to soil salinity (see Table 10.2) as well as several other soil properties affecting conductivity, such as texture, density, and water content. The method involves inserting four or more carefully spaced electrodes into moist soil to make direct measurements of apparent electrical conductivity in the field (EC_a). The depth to which the electrodes sense the EC_a is related to the spacing between the electrodes. Such an on-the-go apparatus for measuring EC_a can be constructed with tillage shanks or with rolling colter blades that serve as electrodes that move through the soil as a tractor pulls the apparatus across a field. This technique is rapid, simple, practical, and gives values that can be correlated with EC_e as well as with other soil properties. This type of apparatus can generate a continuous readout of EC_a measurements as it is driven across a field. If a geopositioning system (GPS) receiver (see Section 19.3) is integrated with the apparatus, the

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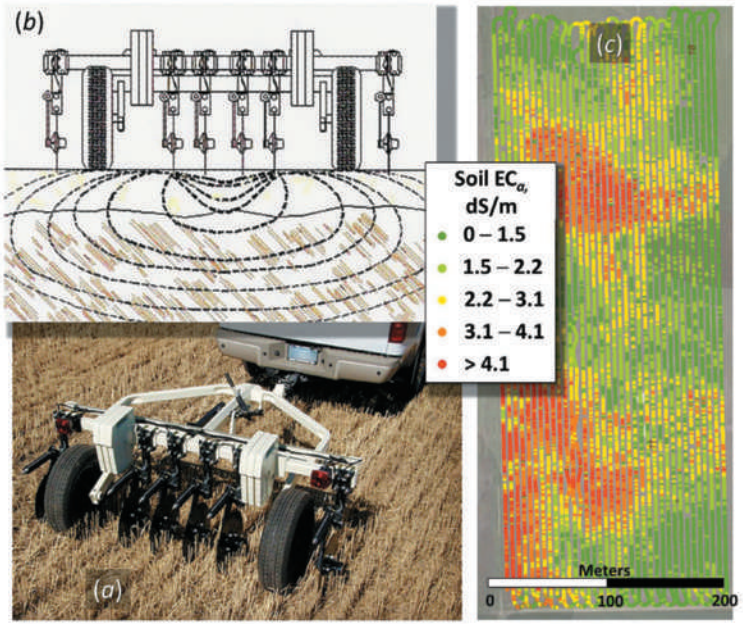

Figure 10.19 *Mapping soil electrical conductivity in the field.* (a) *A mobile apparatus with six rolling colter electrodes and an integrated geopositioning system (GPS) generates a continuous readout of apparent soil conductivity (EC_a) as it is pulled across a field.* (b) *A diagram illustrating how the rolling colters serve as electrodes to send electrical currents through the soil and to detect the flow of these currents as affected by the soil EC.* (c) *Soil electrical conductivity data from a series of transects of the apparatus up and down an agricultural field in North Dakota, USA, are presented as a map showing distinct zones of high EC_a (redder colors) where salinity will likely be a problem for crop growth. In this case, the EC_a readings by the mobile apparatus were highly correlated with lab analyses of saturated paste extract and could be converted into EC_e by multiplying by 2.* [Images (a) and (b) courtesy of Veris Technologies Inc., Salina, KS; image (c) modified from Hopkins et al. (2012) courtesy of David Hopkins, North Dakota State University]

resulting data can be transformed into a map showing the spatial variation of soil salinity (and other soil properties) across a parcel of land (Figure 10.19).

Such measurements reflect the electrical conductivity of all the soil components. Therefore, the EC_a measured is not only related to the salinity of the soil solution, but also to how wet the soil is, the texture of the soil, and a number of other soil properties that influence electrical conductivity. While this fact complicates the data interpretation, when EC_a levels are below those of concern for salinity, it allows EC_a maps to be used for a variety of soil management purposes. The information from these maps can be used as part of **precision agriculture** techniques (see Sections 19.3 and 19.9), which are capable of applying corrective measures tailored to match the degree of salinity in each small part of a large field.

Electromagnetic (EM) Induction. A second rapid field method employs EM induction of electrical current in the body of the soil, the level of which is related to electrical conductivity and, in turn, to soil salinity. A small transmitter coil located in one end of the battery-powered EM instrument generates a magnetic field within the soil. This magnetic field, in turn, induces small electric currents within the soil whose values are related to the soil's conductivity. These small currents generate their own secondary magnetic fields, which can be measured by a small receiving cell in the opposite end of the EM instrument. The EM instrument thus can measure ground EC (designated EC^*_a) to considerable depths in the soil profile without mechanically probing the soil. A handheld model of such an EM conductivity sensor is shown in Figure 10.20. The same type of instrument can be vehicle-mounted and used to rapidly map the soil salinity levels across a field.

It should be noted that each of the methods discussed estimates soil salinity indirectly by measuring electrical conductivity. The values of EC_e, EC_w, EC_s, EC_p, EC_a, or EC^*_a obtained by these procedures will not be identical, however. For example, in highly saline soils EC_a values measured by the multiple-electrode-sensor method are about one-fifth of those measured using the standard saturated paste extract procedure (EC_e). Fortunately, however, these values are all well correlated with each other such that if soil clay and water contents are known, the results from any of the methods can be reasonably well converted to the standard EC_e for interpretation.

Sodium Status

The tendency of certain cations, especially sodium, to cause deterioration of soil physical properties traditionally is termed **sodicity** and is characterized primarily by several equations based on the relative amounts and flocculating ability of the various cations present.

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Figure 10.20 *A portable electromagnetic (EM) soil conductivity sensor used to estimate the electrical conductivity in the soil profile. When placed on the soil surface in the horizontal position* (lower left), *this instrument senses electrical conductivity of the soil down to about 1 m depth. When placed in the vertical position* (as in the inset photo), *the effective depth is about 2 m.* (Photos courtesy of Ray R. Weil)

Two expressions are commonly used to characterize the sodium status of soils. The **exchangeable sodium percentage** (ESP) identifies the degree to which the exchange complex is saturated with sodium:

$$\text{ESP} = \frac{\text{Exchangeable sodium, cmol}_c\text{/kg}}{\text{Cation exchange capacity, cmol}_c\text{/kg}} \times 100 \tag{10.6}$$

ESP levels greater than 15 are associated with severely deteriorated soil physical properties and pH values of 8.5 and above. Figure 10.21 provides two example calculations of ESP.

The **sodium adsorption ratio** (SAR) is a second, more easily measured property that is becoming even more widely used than ESP. The SAR gives information on the comparative concentrations of Na^+, Ca^{2+}, and Mg^{2+} in soil solutions. It is calculated as follows:

$$\text{SAR} = \frac{[Na^+]}{(0.5[Ca^{2+}] + 0.5[Mg^{2+}])^{1/2}} \tag{10.7}$$

where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations (in mmol of charge per liter) of the sodium, calcium, and magnesium ions in the soil solution. An SAR value of 13 for the solution extracted from a saturated soil paste is approximately equivalent to an ESP value of 15. The SAR of a soil extract takes into consideration that the adverse effect of sodium is moderated by the presence of calcium and magnesium ions. The SAR also is used to characterize irrigation water applied to soils (see Section 10.8).

10.5 CLASSES OF SALT-AFFECTED SOILS

Using EC, ESP (or SAR), and soil pH, salt-affected soils are classified as **saline, saline–sodic,** and **sodic** (Figure 10.22). Soils that are not greatly salt-affected are classed as **normal**.

Saline Soils

The processes that result in the accumulation of neutral soluble salts are referred to as **salinization**. The salts are mainly chlorides and sulfates of calcium, magnesium, potassium, and sodium. The concentration of these salts sufficient to interfere with plant growth (see Section 10.7) is generally defined as that which produces an electrical conductivity in the saturation extract (EC_e) greater than 4 dS/m. However, some sensitive plants are adversely affected when the EC_e is only about 2 dS/m.

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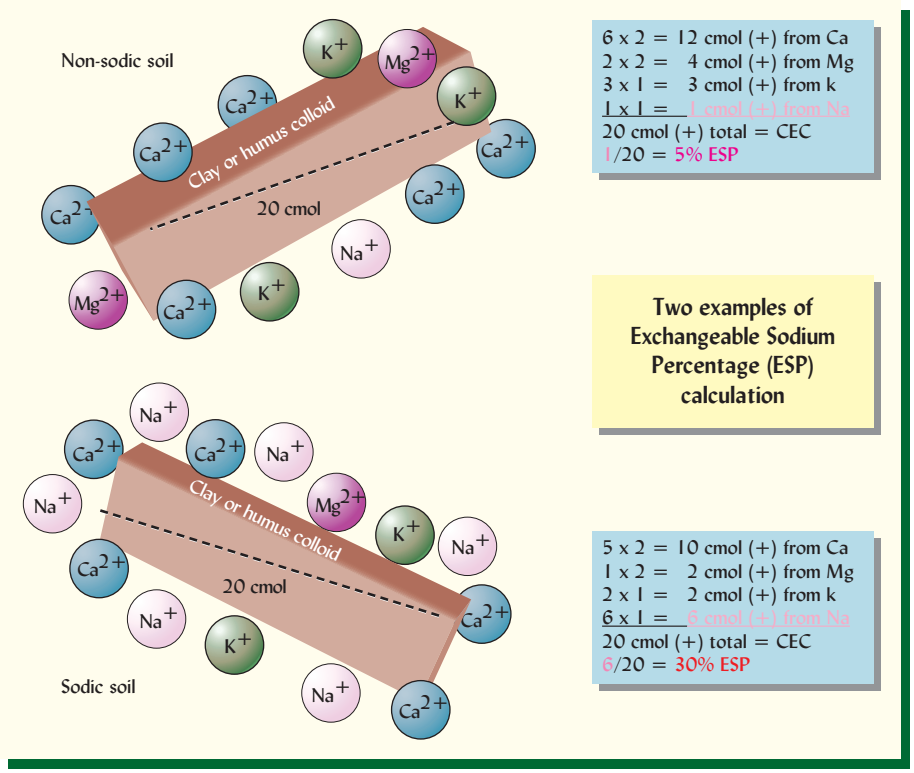

Figure 10.21 *An illustration of exchangeable sodium percentage calculation for two soils, one sodic the other not.* (Diagram courtesy of Ray R. Weil)

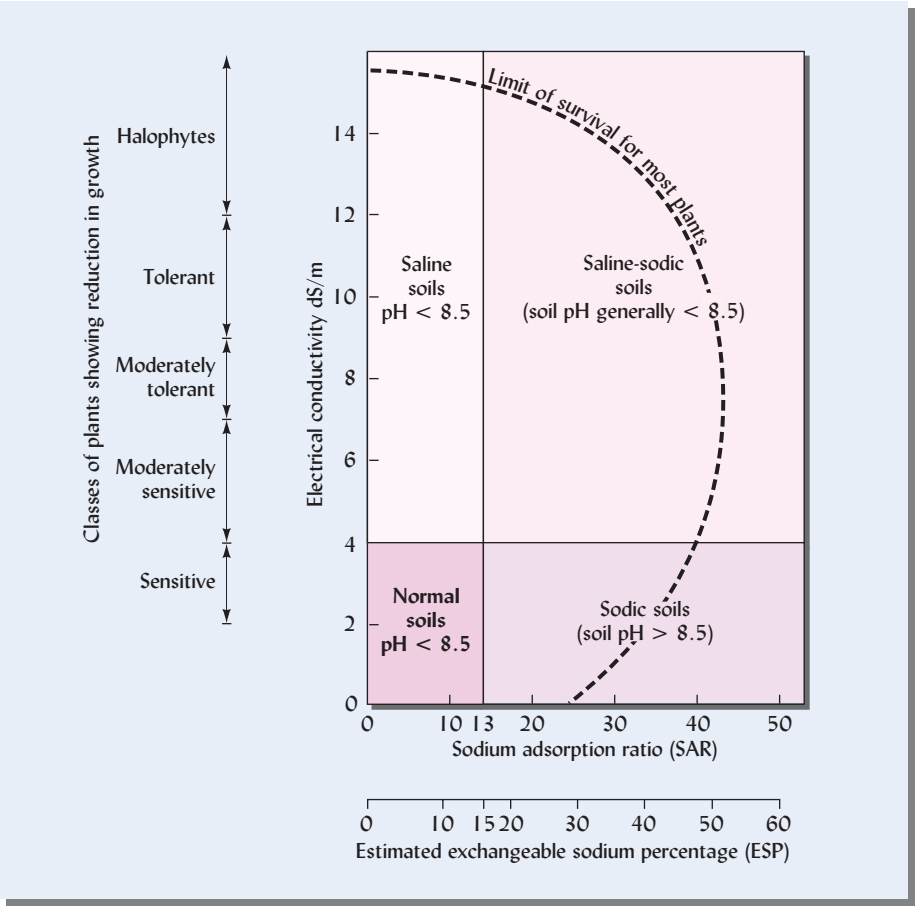

Figure 10.22 *Diagram illustrating the classification of normal, saline, saline–sodic, and sodic soils in relation to soil pH, electrical conductivity, sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP). Also shown are the ranges for different degrees of sensitivity of plants to salinity.*

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Saline soils are those soils that contain sufficient salinity to give EC_e values greater than 4 dS/m, but have an ESP less than 15 (or an SAR less than 13) in the saturation extract. Thus, the exchange complex of saline soils is dominated by calcium and magnesium, not sodium. The pH of saline soils is usually below 8.5. Because soluble salts help prevent dispersion of soil colloids, plant growth on saline soils is not generally constrained by poor infiltration, aggregate stability, or aeration. In many cases, the evaporation of water creates a white salt crust on the soil surface (see Figures 10.14–10.16), which accounts for the name ***white alkali*** that was previously used to designate saline soils.

Saline–Sodic Soils

Soils that have both detrimental levels of neutral soluble salts (EC_e greater than 4 dS/m) *and* a high proportion of sodium ions (ESP greater than 15 or SAR greater than 13) are classified as **saline–sodic soils** (see Figure 10.22). Plant growth in these soils can be adversely affected by both excess salts and excess sodium levels.

Saline–sodic soils exhibit physical conditions intermediate between those of saline soils and those of sodic soils. The high concentration of neutral salts moderates the dispersing influence of the sodium. The salts provide excess cations that move in close to the negatively charged colloidal particles, thereby reducing their tendency to repel each other, or to disperse. The salts, therefore, help keep the colloidal particles associated with each other in floccules and aggregates.

Unfortunately, this situation is subject to rather rapid change if the soluble salts are leached from the soil, especially if the SAR of the leaching waters is high. In such a case, salinity will drop, but the exchangeable sodium percentage will increase, and the saline–sodic soil will become a sodic soil.

Sodic Soils

Definition. Sodic soils are, perhaps, the most troublesome of the salt-affected soils. While their levels of neutral soluble salts are low (EC_e less than 4.0 dS/m), they have relatively high levels of sodium on the exchange complex (ESP and SAR values are above 15 and 13, respectively). Some sodic soils in the order Alfisols (Natrustalfs) have a very thin A horizon overlying a clayey layer with columnar structure, a profile feature closely associated with high sodium levels (Figure 10.23). The pH values of sodic soils generally exceed 8.5, rising to 10 or higher in some cases. As explained in Section 10.2, these extreme pH levels are largely due to the fact that sodium carbonate is much more soluble than calcium or magnesium carbonate and so maintains high concentrations of CO_3^{2-} and HCO_3^- in the soil solution. The pH of sodic soils may not reach such high levels where the main soluble anions are chlorides and/or sulfates, such as in certain nonalkaline sodic soils in Australia.

The extremely high pH levels in sodic soils may cause the soil organic matter to disperse and/or dissolve. The dispersed and dissolved humus moves upward in the capillary water flow and, when the water evaporates, can give the soil surface a black color. The name ***black alkali*** was previously used to describe these soils. Sometimes located in small areas

Figure 10.23 *The upper profile of a sodic soil (a Natrustalf) in a semiarid region of western Canada. Note the thin A horizon (knife handle is about 12 cm long) underlain by columnar structure in the natric (Btn) horizon. The white, rounded "caps" of the columns are comprised of soil dispersed because of the high sodium saturation. The dispersed clays give the soil an almost rubbery consistency when wet.* [Photo courtesy of Agriculture and Agri-Food Canada]

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called ***slick spots***, sodic soils may be surrounded by soils that are considerably more productive. Plant growth on sodic soils is often constrained by specific toxicities of Na^+, OH^-, and HCO_3^- ions. However, the main reason for the poor plant growth—often to the point of complete barrenness—is that few plants can tolerate the extremely poor soil physical conditions and slow permeability to water and air that accompany clay dispersion in sodic soils. We will next take a closer look at this chemically induced physical degradation that is such a widespread phenomenon of great importance, even in many soils that do not fall within the formal definition of sodic.

10.6 PHYSICAL DEGRADATION OF SOIL BY SODIC CHEMICAL CONDITIONS

The high sodium and low salt levels in sodic soils (and, to a lesser degree, in some "normal" soils) can cause serious clay dispersion, degradation of aggregate structure, and loss of macroporosity such that the movement of water and air into and through the soil is severely restricted. This structural degradation is most commonly measured in terms of the readiness of water movement—the saturated hydraulic conductivity of the soil (Figure 10.24 and Section 5.5). Often sodic soils exhibit such low K_{sat} values that the infiltration rate is reduced almost to zero, causing water to form puddles rather than soak into the soil. The soil is therefore said to be *puddled*, a condition characteristic of sodic soils. Physically, the puddled condition of a sodic soil is much like that of a rice paddy soil in which a farmer has mechanically destroyed the soil structure in order to be able to keep the paddy inundated with water (see Section 4.6).

Slaking, Swelling, and Dispersion

In most soils, the low permeability related to sodic conditions has three underlying causes. First, exchangeable sodium increases the tendency of aggregates to break up or *slake* upon becoming wet. The clay and silt particles released by slaking aggregates clog soil pores as they are washed down the profile. Second, when expanding-type clays (e.g., montmorillonite) become highly Na^+-saturated, their degree of swelling is increased. As these clays expand, the larger pores responsible for water drainage in the soil are squeezed shut. Third, and perhaps most important, sodic conditions—the combination of high sodium and low ionic strength (dissolved salt concentrations)—lead to soil dispersion. Dispersion is the opposite of flocculation. In normal soils, clay particles flocculate together, giving rise to tiny clumps (floccules) that create pores between them and promote the formation of larger aggregates (see Section 4.5). In dispersed soils, the clay particles separate from one another, creating an almost gel-like condition. While these phenomena are most pronounced in sodic soils, they can occur to some degree in other dry-region soils subjected to low electrolyte water (e.g., rain!) and/or moderately high levels of monovalent cations (Figure 10.25).

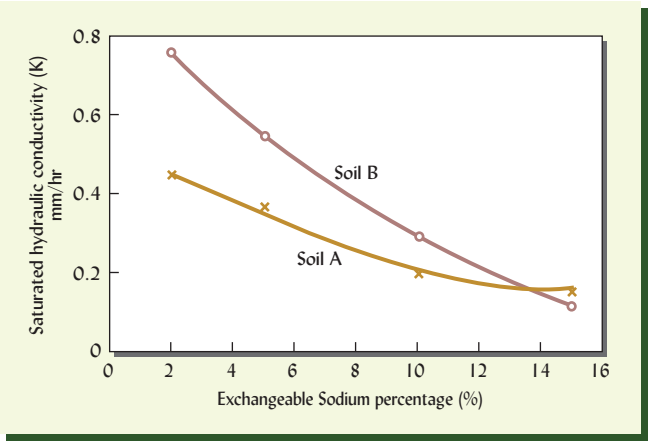

Figure 10.24 *Effect of increasing exchangeable sodium percentage (ESP) on the saturated hydraulic conductivity of two Vertisols in Italy. Note the steady decline in conductivity with increasing ESP and the very low conductivity at ESP ≈15%. Such low conductivity will slow infiltration to the point that water will form puddles on the surface rather than soak into the soil. Hence the term* puddled condition. [Redrawn from Crescimanno et al. (1995)]

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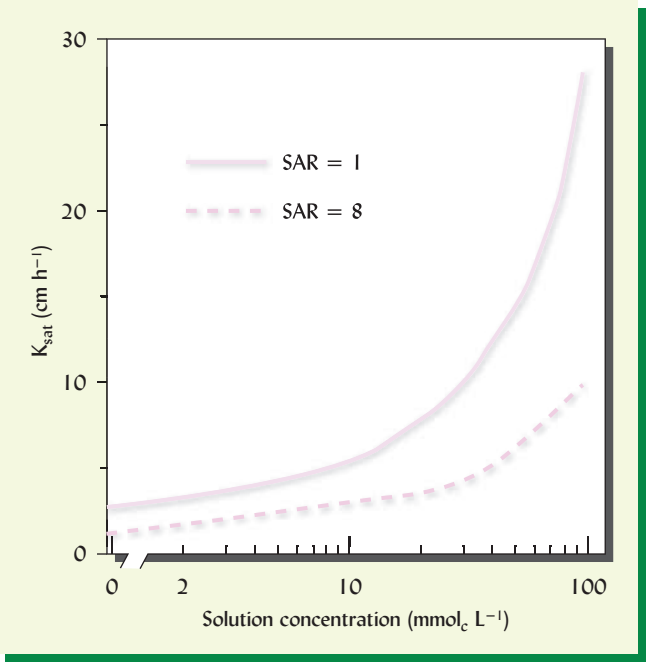

Figure 10.25 *Opposing influences of sodium absorption ratio (SAR) and solution electrolyte (salt) concentration on the saturated hydraulic conductivity (K_{sat}) of a clay loam soil (an Aridisol) with smectitic clay mineralogy. Increasing solution electrolyte concentration stimulated clay flocculation and reduced clay swelling, both effects that promote more rapid flow of water through the soil (higher K_{sat}). Note that the solution concentration ranged from 0 (distilled water) to 100 mmol$_c$ L^{-1}, the highest concentration being quite saline—roughly equivalent to 5000 mg/L TDS or $EC_w \approx 7$ dS/m. In nearly pure water, K_{sat} was very low, regardless of the SAR level. When the solution concentration was stronger, a moderately high SAR (recall that SAR ≈13 defines a sodic soil) reduced the K_{sat} from nearly 30 to less than 10 cm h^{-1}. These effects are explained conceptually by Figures 10.26 and 10.29 in terms of dispersion and flocculation.* [Redrawn from Mace and Amrhein (2001) with permission from the Soil Science Society of America]

Two Causes of Soil Dispersion

Two chemical conditions promote dispersion. One is a high proportion of Na^+ ions on the exchange complex. The second is a low concentration of electrolytes (salt ions) in the soil water.

High Sodium. Exchangeable Na^+ ions promote dispersion for two reasons. First, because of their single charge and large hydrated size, they are attracted only weakly to soil colloids, and so they spread out to form a relatively broad swarm of ions held in very loose outer-sphere complexes around the colloids (see Section 8.7). Second, compared to a swarm of divalent cations (which have two positive charges each), twice as many monovalent ions (with only one charge each) are needed to provide enough positive charges to counter the negative charges on a clay surface. As illustrated in Figure 10.26, the layer of exchangeable monovalent Na^+ ions is therefore much thicker than that which would form with the more strongly attracted divalent ions such as Ca^{2+}. The highly sodium-saturated colloids are kept so far apart that the forces of cohesion cannot come into play to attract one colloid surface to another. Instead, the poorly balanced electronegativity of each colloidal surface repels other electronegative colloids, and the soil becomes dispersed. Figure 10.26 therefore illustrates the relationships expressed mathematically by the SAR (Eq. (10.7). Box 10.2 considers some advances in our understanding of how the various mono- and di-valent cations affect flocculation and dispersion.

Low Salt Concentration. A low ionic concentration in the bulk soil solution simultaneously increases the gradient causing exchangeable cations to diffuse away from the clay surface while it decreases the gradient causing anions to diffuse toward the clay (Figure 10.29). The result is a thick ionic layer or swarm of absorbed cations. Adding *any* soluble salt would increase the ionic concentration of the soil solution and encourage the opposite effects—resulting in a compressed ionic layer that allows the clay particles to come close enough together to form floccules. The dissolved salt concentration that is just high enough to cause flocculation and prevent dispersion is termed the *flocculation value*. This value increases as the proportion of exchangeable Na^+ increases, illustrating that the effect of sodium can be counteracted by increasing the dissolved salt concentration and that the damaging effects of sodium are greatest when salt concentra-

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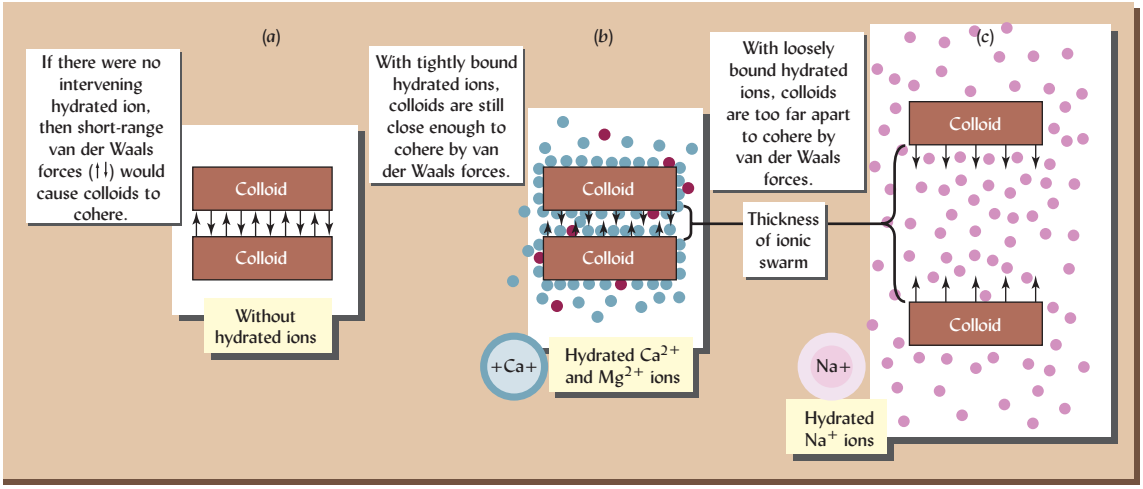

Figure 10.26 *Conceptual diagrams showing how the type of cations present on the exchange complex influences clay dispersion. If colloids could approach closely (a), they would be held together (cohere) by short-range van der Waals forces. In soil, the colloids are surrounded by a swarm of hydrated exchangeable ions, which prevent the colloids from approaching so closely. If these are strongly attracted calcium and magnesium ions (b), they do not keep the colloids very far apart, so cohesive forces still have some effect. However, if they are sodium ions (c), the more spread-out ionic swarm keeps the colloids too far apart for cohesive forces to come into play. Sodium ions cause a spread-out ion swarm for two reasons: (1) their large hydration shell of water allows them to be only loosely attracted to the colloids, and (2) twice as many monovalent Na^+ ions as divalent (Ca^{2+} or Mg^{2+}) ions are attracted to a given colloid charge. When the colloid particles are separated from each other, the soil is in a dispersed condition.* (Diagrams courtesy of Ray R. Weil)

BOX 10.2

CATION RATIOS AFFECT SOIL STRUCTURAL STABILITY

The SAR has served since the 1950s as the principal way of relating soil exchangeable cations to clay dispersion and structural stability and the problems of sodic soils. Over the years, soil scientists have noted that high amounts of other monovalent ions such as potassium (K^+) can also promote soil structure degradation, though less so than sodium. Therefore, some soil scientists have suggested that the SAR should be modified to include the sum of (Na^+) + (K^+) in the numerator of Eq. (10.7). Excessive K^+ may originate from soil minerals or irrigation water as typically is the case for Na^+, but it may also come from over-application of potassium fertilizer or from heavy use of legume mulches or manure generated by animals fed a high K diet, such as the alfalfa-rich diets used by many dairy farms.

In addition, because Mg^{2+} does not exert as strong a flocculating influence on clays as does Ca^{2+}, some researchers have suggested the Mg^{2+} in the SAR equation should be given less weight than the Ca^{2+}. The relatively greater flocculating power of Ca^{2+} as compared to Mg^{2+} ions is illustrated in Figure 10.27. The clay flocculating power of the four main cations in salt-affected soils (relative to sodium) have been estimated to be: Na = 1.0 , K = 1.8, Mg = 27, and Ca = 45. Thus both monovalent ions, Na and K, have so little flocculating power that they allow clays to disperse, while Mg and Ca both cause clay flocculation,

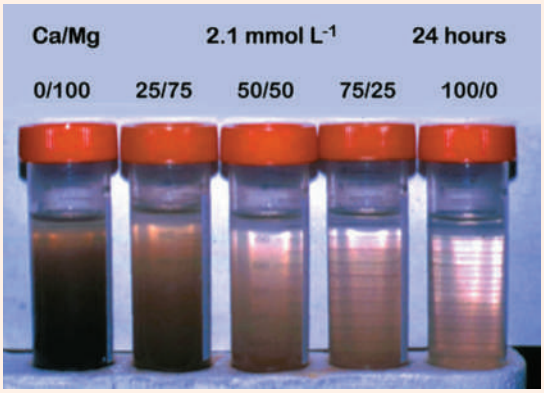

Figure 10.27 *The effect of Ca/Mg ratio on flocculation of a clay fraction of Catlin soil (Argiudolls) in suspension with low content of dissolved salt (8.4 mmol L^{-1} ionic strength). The samples were shaken and then allowed to settle for 24 hours before the photo was taken. In the leftmost tube where the soil was 100% Mg-saturated with no Ca, most of the clay was dispersed (unflocculated) and still in suspension. The tubes farther to the right had greater proportions of exchangeable Ca and show greater flocculation and settling of the clay.* [From Dontsova and Norton (2002). Photo courtesy of Katerina Dontsova]

(continued)

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BOX 10.2

CATION RATIOS AFFECT SOIL STRUCTURAL STABILITY

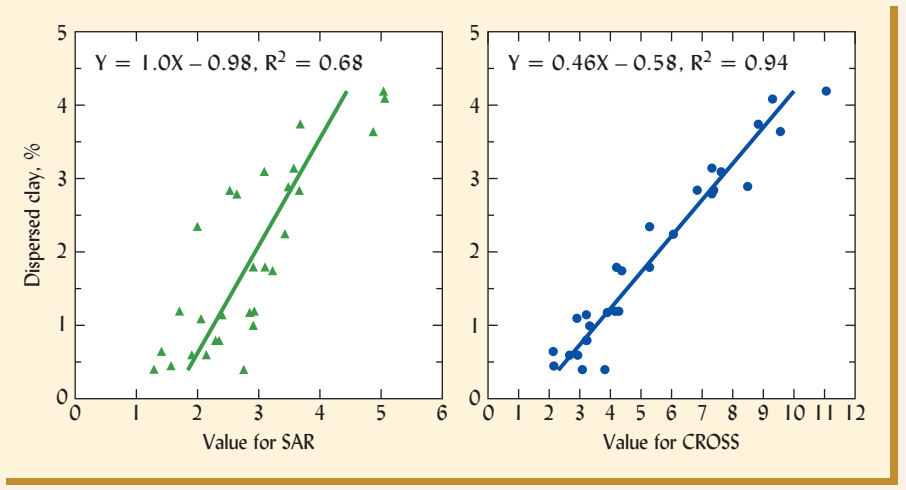

Figure 10.28 *These graphs confirm, using 29 clay soils from Australia, that the CROSS expression is better correlated with clay dispersion than the simpler SAR equation. The R^2 values shown after the linear regression equations in the graph indicate that the SAR accounts for 0.68 (or 68%) and the CROSS accounted for 0.94 (or 98%) of the variation in dispersion among the 29 soils.* [Graphed from data in Rengasamy and Marchuk (2011)]

but Ca considerably more so. Researchers in Australia and elsewhere have defined a new soil property that uses all four of these cations and weighs their concentrations according to their relative flocculation power. This property is termed cations ratio of structural stability (CROSS) and is expressed in a form analogous to SAR:

$$CROSS = \frac{Na + 0.56K}{\sqrt{Ca + 0.6Mg}} \qquad (10.8)$$

where the concentrations of these ions (Na, K, Ca, and Mg) are expressed in millimole of charge/L in 1:5 soil:water extracts. The CROSS equation reflects theoretical and empirical observations that potassium ions are about 0.56 times as dispersive as sodium ions, and that magnesium ions are about 0.6 times as flocculating as calcium ions. By taking into account all four major cations and their relative flocculating power, the CROSS appears to predict clay dispersion and physical problems of sodic soils more accurately than the traditional SAR (Figure 10.28). Being based on cation concentrations in a 1:5 soil:water extract rather than in a saturated paste extract, the CROSS certainly can be measured more easily and rapidly than the SAR.

tions are lowest. Figure 10.30 shows that the flocculation value for a given level of sodium depends on the type of clay present, the micaceous clays (e.g., illite) being more susceptible to dispersion (i.e., requiring a higher ionic concentration to prevent dispersion) than the smectites (e.g., montmorillonite requiring a higher).

It is worth remembering that *low salt (ion) concentrations and weakly attracted ions (e.g., sodium) encourage soil dispersion and puddling, while high salt concentrations and strongly attracted ions (e.g., calcium) promote clay flocculation and soil permeability.*

10.7 BIOLOGICAL IMPACTS OF SALT-AFFECTED SOILS[7]

How Salts Affect Plants

Plants respond to the various types of salt-affected soils in different ways. In addition to the nutrient-deficiency problems associated with high pH (see Section 10.1), high levels of soluble salts affect plants by two primary mechanisms: **osmotic effects** and **specific ion effects**.

[7]Effects of salinity and water stress are reviewed by Munns (2002) for plants and by Yan et al. (2016) for microorganisms.

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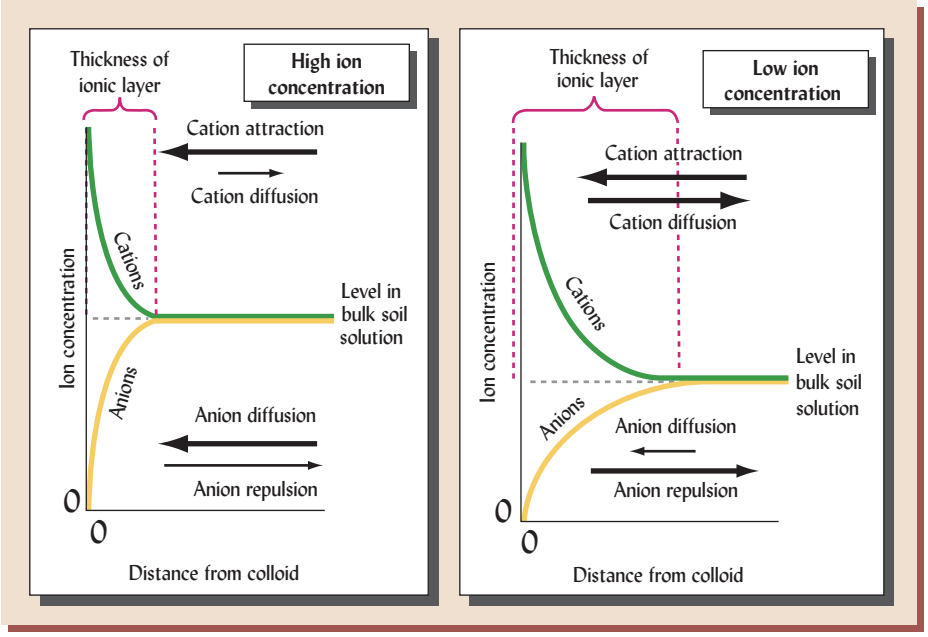

Figure 10.29 *Ion (electrolyte) concentration in the soil solution influences soil dispersion. When the ion concentration is high (left), anions diffuse more strongly toward the colloid surface because their concentration gradient is steeper—that is, the difference is large between the anion concentration at the clay surface (nearly zero) and in the bulk soil solution. Since cation concentration is very high at the clay surface, an increased ion concentration in the bulk solution diminishes the cation concentration gradient. Therefore, the tendency is weaker for cations to diffuse away from the clay surface. To summarize: with higher salt concentration, cations stay closer and anions come closer to the clay; hence the ion swarm is compressed and clay particles can get close enough to one another to flocculate. When the ionic concentration is low (right), the opposite trends pertain: the ion swarm becomes more diffuse, and the colloids become dispersed.* (Diagrams courtesy of Ray R. Weil)

Osmotic Effects. Soluble salts lower the osmotic potential of the soil water (see Section 5.3), making it more difficult for roots to remove water from the soil. For established plants (and soil bacteria), this condition requires the expenditure of more energy on osmotic adjustments—accumulating organic and inorganic solutes to lower the osmotic potential *inside* the cells to counteract the low osmotic potential of the soil solution outside. The lost energy results in reduced growth. For annual crops, the lowered osmotic potential can result in more frequent wilting and reduced water uptake from the soil profile.

Plants are most susceptible to salt damage in the early stages of growth. Salinity may delay, or even prevent, the germination of seeds (Figure 10.31). Young seedlings may be killed by saline conditions that older plants of the same species could tolerate. The radicle (root precursor) of a germinating seed appears to be particularly sensitive to salinity. As young root cells encounter a soil solution high in salts, they may lose water by osmosis to the more

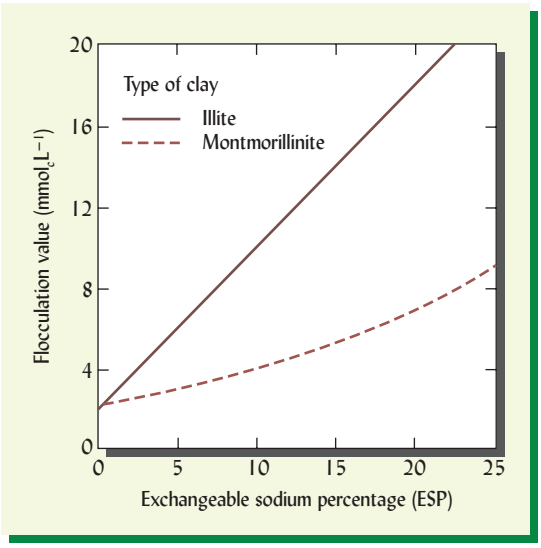

Figure 10.30 *Effect of exchangeable sodium percentage (ESP) on the "flocculation value" for two clays. The flocculation value was defined as the minimum ionic strength needed to cause flocculation and prevent dispersion. Note that when sodium accounts for a greater percentage of the exchangeable ions, a higher ionic strength (i.e., salt concentration) is needed to prevent clay dispersion. The effect is more pronounced for illite clay than for montmorillonite clay (see Section 8.3).* [Based on data cited in Evangelou and Phillips (2005)]

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concentrated soil solution. The cells then collapse. The same can happen to the tender young stems of certain seedlings.

Specific Ion Effects. The kind of salt can make a big difference in how plants respond to salinity. Certain ions, including Na^+, Cl^-, $H_3BO_4^-$, and HCO_3^- are quite toxic to many plants. However, as we will see, plant species, and even strains within a species, differ widely in their sensitivity to these ions. In addition to specific toxic effects, high levels of Na^+ can cause imbalances in the uptake and utilization of other cations. For example, Na^+ competes with the essential nutrient ion K^+ in the process of transport across the cell membrane during uptake, making it difficult for plants to obtain the K^+ they need from saline–sodic or sodic soils. The presence of adequate Ca^{2+} helps the plant to discriminate against Na^+ and for K^+. This is but one example of how the balance of specific ions in saline soils can be as important to plant health as the total salt concentrations.

Physical Effects of Sodicity. Deterioration of physical properties is also a major factor in determining which plants can grow in sodic soils. The colloidal dispersion caused by sodicity may harm plants in at least two ways: (1) oxygen becomes deficient due to the breakdown of soil structure and the very limited air movement that results, and (2) water relations are poor due largely to the very slow infiltration and percolation rates.

Plant Symptoms. In response to excessive soil salinity, many plants become severely stunted and exhibit small dark-bluish green leaves with dull surfaces. High levels of sodium or chloride typically produce scorching or necrosis of the leaf margins and tips (see Figure 10.31, *inset*). These symptoms appear first and most severely on the oldest leaves as these have been transpiring water and accumulating salts for the longest period. Salt-stressed plants may also lose their leaves prematurely.

Selective Tolerance of Higher Plants to Saline and Sodic Soils

Satisfactory plant growth on salty soils depends on a number of interrelated factors, including the physiological constitution of the plant, its stage of growth, and its rooting habits. For

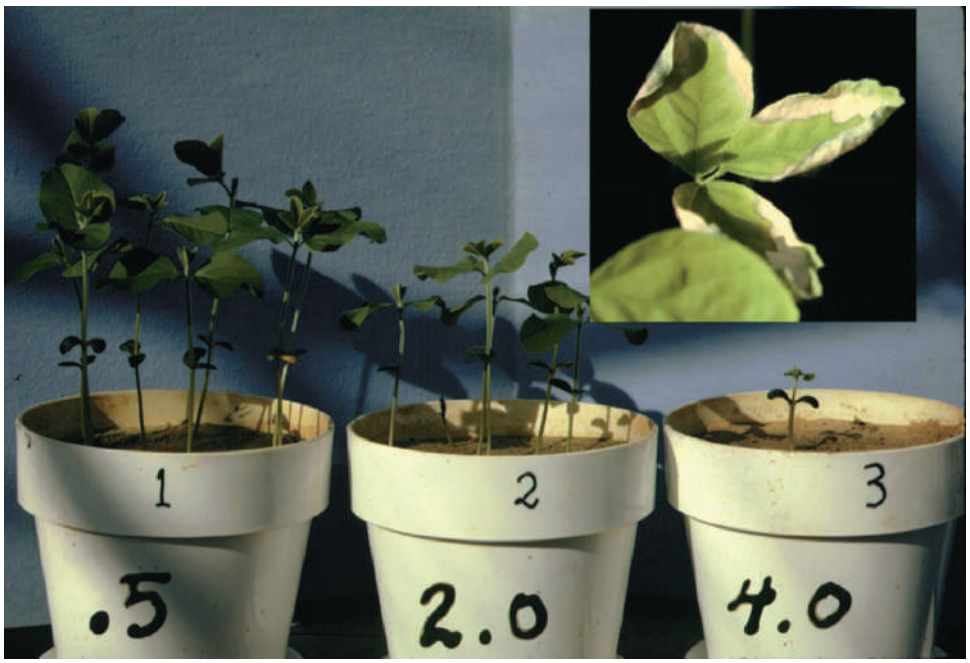

Figure 10.31 *Foliar symptoms on oldest leaves (*inset*), reduced germination, and stunted growth of soybean plants with increasing levels of soil salinity due to additions of NaCl to a sandy soil. The large numbers written on the pots indicate the electrical conductivity (EC_e) of the soil. Note that serious growth reductions occurred for this sensitive cultivar even at EC_e levels considered "normal." The soybean cultivar used (Jackson) is more sensitive to salinity than most other cultivars of soybean.* (Photos courtesy of Ray R. Weil)

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example, older plants, deeper-rooted plants are generally more tolerant to salt-affected soils than younger, more shallow-rooted ones.

Plant Sensitivity. Figure 10.32 shows how soil salinity, as measured by electrical conductivity (EC_e), affects the relative productivity of four general salinity-tolerance groups. Table 10.3 groups selected plants according to this classification. Note that trees, shrubs, grasses, fruits, vegetables, and field crops are included in the different categories.

Approximately 1% of plant species are ***halophytes***, plants that can tolerate high levels of salinity, some as high as sea water. They are quite a diverse group and plant scientists speculate that many could be domesticated into crops for a salt-tolerant agriculture producing food, feed, fiber, and biofuels on the world's increasing area of salinized land. They are also valuable for restoring disturbed or degraded land under saline conditions.

Genetic Improvements. Plant breeders have been able to develop new crop strains with salt tolerance greater than that possessed by conventional varieties. A major advance was made by the discovery of a single gene that enables halophytes to sequester high amounts of Na^+ in their cellular vacuoles (large, membrane-enclosed storage structures inside individual cells). In the vacuole, the Na^+ ions can act to the plant's advantage by contributing to low internal osmotic potential while remaining isolated from cellular systems that are susceptible to Na^+ toxicity. Work is underway to use genetic engineering techniques to transfer this gene to economically important plants, with the aim of producing crops that can tolerate saline soils and the use of salty water for irrigation. In contrast, another gene found in salt-tolerant relatives of wheat enables the plant to exclude Na^+ ions altogether. Plant selection and improvement will almost certainly make important contributions to food production on salt-affected soils in the future. However, improved plant tolerance must not be viewed as a substitute for proper salinity control, as discussed in Section 10.9.

Salt Problems Not Related to Arid Climates

Deicing Salts. In areas where deicing salts are used to keep roads and sidewalks free of snow and ice during winter months, these salts may impact roadside soils and plants. Repeated application of deicing salts can result in salinity levels sufficiently high as to adversely affect plants and soil organisms living alongside highways or sidewalks. Figure 10.33 illustrates tree damage from such treatment. In humid regions, such salt contamination is usually temporary, as the abundant rainfall leaches out the salts in a matter of weeks or months. To reduce the

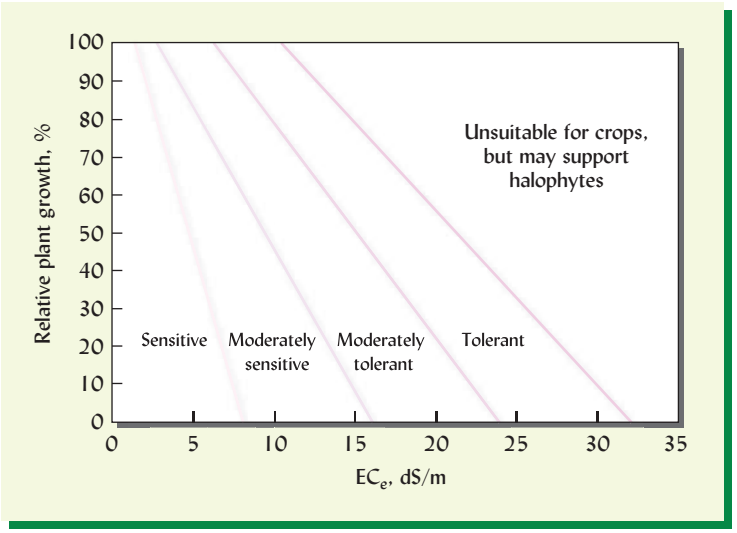

Figure 10.32 *Relative productivity of five groups of plants classified by their sensitivity to salinity as measured by electrical conductivity of the soil. See Table 10.3 for examples of plants in each sensitivity class.* [From Maas and Grattan (1999); with permission of the American Society of Agronomy]

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Table 10.3
RELATIVE SALT TOLERANCE OF SELECTED PLANTS
Approximate EC_e resulting in a 10% reduction in plant growth for the most sensitive species in each column.

Tolerant, 12 dS/m	Moderately tolerant, 8 dS/m	Moderately sensitive, 4 dS/m	Sensitive, 2 dS/m
Alkali grass, Nutall	Ash (white)	Alfalfa	Alders
Alkali sacaton	Asparagus	Arborvitae	Almond
Barley (grain)	Aspen	Boxwood	Apple
Bent grass	Barley (forage)	Broad bean	Apricot
Bermuda grass	Beet (garden)	Cabbage	Azalea
Bougainvillea	Black cherry	Celery	Beech
Boxwood, Japanese	Broccoli	Clover (alsike, ladino, red,	Bean
Canola (rapeseed)	Bromegrass	strawberry, and berseem)	Birch
Cotton	Cedar (red)	Corn	Blackberry
Date	Cowpea	Cucumber	Carrot
Guayule Jojoba	Elm	Dallas grass	Dogwood
Kenaf	Fescue (tall)	Grape	Elm (American)
Oak (red and white)	Honeysuckle	Hickory (shagbark)	Hemlock
Oleander	Hydrangea	Lettuce	Hibiscus
Olive	Juniper	Locust (black)	Larch
Prostrate kochia	Kale	Maple (red)	Linden
Redwort	Locust (honey)	Pea	Maple (sugar and red)
Rescue grass	Oak (red and white)	Peanut	Onion
Rosemary	Oats	Radish	Orange
Rugosa Rye (grain)	Orchard grass	Rice (paddy)	Peach
Salt grass (desert)	Pomegranate	Soybean (sens. var.)	Pear
Sugar beet	Ryegrass (perennial)	Squash	Pine (red and white)
Tamarix	Safflower	Sugar cane	Pineapple
Wheat grass (crested)	Sorghum	Sweet potato	Potato
Wheat grass (tall)	Soybean (tol. var.)	Timothy	Raspberry
Wild rye (Russian)	Squash (zucchini)	Tomato	Rose
Willow	Sudan grass	Turnip	Star jasmine
	Wheat	Vetch	Strawberry
	Winged bean	Viburnum	Tomato

specific chemical and physical problems associated with sodium salts, many municipalities have switched from NaCl to KCl or $MgCl_2$ for deicing purposes. Sand can be used to improve traction, thereby reducing the need for deicing salt.

Containerized Plants. Salinity can also be a serious problem for potted plants, particularly perennials that remain in the same pot for long periods (Figure 10.16, *left*). Greenhouse operators producing containerized plants must carefully monitor the quality of the water used for irrigation. Salts in the water, as well as those applied in fertilizers, can build up if care is not taken to flush them out occasionally with excess water. Chlorinated urban tap water used for indoor plants should be left overnight in an open container to allow some of the dissolved chlorine to escape as chlorine gas, thus reducing the load of Cl^- ions added to the potting soil.

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Figure 10.33 *Salts spread on roadways to melt winter ice and snow in cold regions can cause salt injury to vegetation growing in roadside soils. (a) Localized salt concentrations are visible on the soil surface some three months after the last salt application. Dieback of the maple trees is also evident. (b) Close-up view of chlorotic and dead leaf-margin tissue caused by deicing salts on a dogwood tree. (c) A bag of magnesium chloride based deicing salts.* (Photos courtesy of Ray R. Weil)

10.8 WATER-QUALITY CONSIDERATIONS FOR IRRIGATION[8]

Whether in a single field or in a large regional watershed, understanding the **salt balance** is a basic prerequisite for wise management of salt-affected soils and waters. To achieve salt balance in a soil, the amount of salt coming in must be matched by the amount being removed. Meeting this condition is a fundamental challenge to the long-term sustainability of irrigated agriculture. In irrigated areas, this principally means managing the quality and amount of the irrigation water brought in and the quality and amount of soil drainage water removed.

Irrigation Water Quality. Table 10.4 provides some guidelines on water quality for irrigation. Monitoring the chemical quality of water added to salt-affected soils is a prime management strategy. For example, when dealing with a saline–sodic soil, water that is too low in salts, such as rainwater, can hasten the change from saline–sodic to sodic soil conditions. Rain not only leaches soluble salts from the upper few centimeters of soil, but the impact of the raindrops encourages dispersion of the soil colloids, an initial step in the process of sodic soil development.

If the salt content of irrigation water is high, salt balance will be difficult to achieve. However, even very salty water can be used successfully if soils are sufficiently well drained to allow careful management of salt inputs and outputs. Where irrigation water is low in salts but has a high SAR, the formation of sodic soils is likely to accelerate. In addition, irrigation water high in carbonates or bicarbonates can reduce Ca^{2+} and Mg^{2+} concentrations in the soil solution by precipitating these ions as insoluble carbonates. This leaves a higher proportion of Na^{+} in the soil solution and can increase its SAR, moving the soil toward the sodic class.

Drainage Water Salinity. Since some portion of added water must be drained away to combat salt buildup, the quality and disposition of *irrigation drainage waters* must also be carefully monitored and controlled to minimize potential harm to downstream users and habitats.

[8]For contrasting overviews of water-quality and conservation problems facing advanced irrigated agriculture, see Letey (2000) and Gleick et al. (2011).

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Table 10.4
WATER-QUALITY GUIDELINES FOR IRRIGATION
Note that higher total salinity (EC_w) in irrigation water compensates, somewhat, for increasing sodium hazard (SAR). Also note that water low in salts (low EC_w) avoids problems of restricted water availability to plants, but it may worsen soil physical properties, especially if the SAR is high.

		Degree of restriction on use		
Water Property	**Units**	**None**	**Slight to moderate**	**Severe**
		Salinity (affects crop water availability)		
EC_w	dS/m	<0.7	0.7–3.0	>3.0
TDS	mg/L	<450	450–2000	>2000
		Physical structure and water infiltration (evaluate using EC_w and SAR together)		
SAR = 0–3 and EC_w =	dS/m	>0.7	0.7–0.2	<0.2
SAR = 3–6 and EC_w =	dS/m	>1.2	1.2–0.3	<0.3
SAR = 6–12 and EC_w =	dS/m	>1.9	1.9–0.5	<0.5
SAR = 12–20 and EC_w =	dS/m	>2.9	2.9–1.3	<1.3
SAR = 20–40 and EC_w =	dS/m	>5.0	5.0–2.9	<2.9
		Sodium (Na) specific ion toxicity (affects sensitive crops)		
Surface irrigation	mmol/L	<3	3–9	>9
Sprinkler irrigation	mmol/L	<3	>3	
		Chloride (Cl) specific ion toxicity (affects sensitive crops)		
Surface irrigation	mmol/L	<4	4–10	>10
Sprinkler irrigation	mmol/L	<3	>3	
		Boron (B) specific ion toxicity (affects sensitive crops)		
	mg/L	<0.7	0.7–3.0	>3.0

Modified from Abrol et al. (1988) with permission of the Food and Agriculture Organization of the United Nations.

In any irrigation system, the drainage water leaving a field will be considerably more concentrated in salts than the irrigation water applied to the same field (Figure 10.34 explains why). What to do with the increasingly saline drainage water presents a major challenge to the sustainability of irrigated agriculture.

Different irrigation projects take different approaches, but rarely is the problem solved without some downstream environmental damage. Perhaps the most efficient approach is to collect the drainage water, keep it isolated from the relatively high-quality canal water, and reuse it to irrigate a more salt-tolerant crop in a lower field. This approach provides both high-quality canal water and lower-quality drainage water for use on appropriate crops. Generally, the salt-tolerant crops are less valuable than the more salt-sensitive ones (e.g., the yield of salt-tolerant cotton from 1 ha is worth much less than the yield of salt-sensitive tomato); still, recycling drainage water saves money as well as water. Often some fresh water must be mixed with the recycled drainage water to bring its salinity level down to what can be tolerated by even the salt-tolerant crop (see Figure 10.35). After several cycles of reuse, the drainage water must be disposed of, as it will have become too saline for irrigating even the most salt-tolerant species.

A more common (though less water-efficient) approach is to route the drainage water back into the canal. This mixes the poor-quality drainage water with the high-quality canal water, improving the one but degrading the other. Again, after several cycles, the downstream water becomes too saline for use and must be disposed of (or treated to remove the salts—a very expensive process). In many cases, the irrigation wastewater is eventually channeled into shallow ponds that allow the water to evaporate and the salts to collect.

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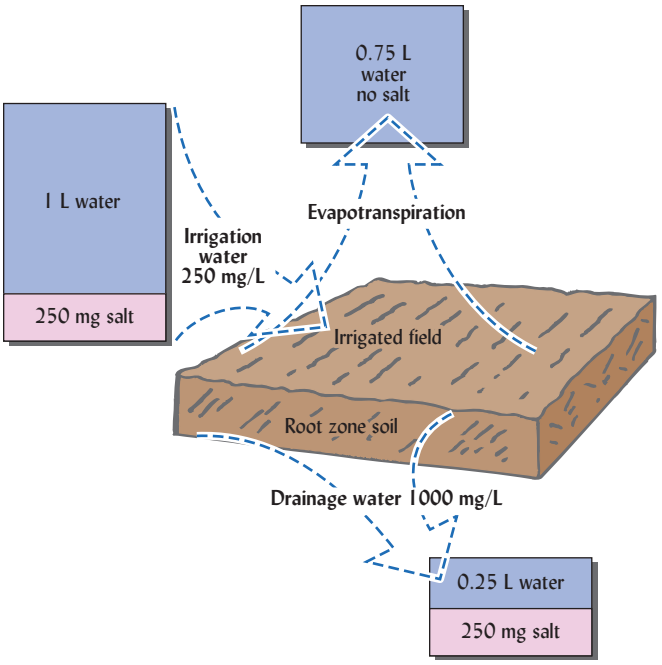

Figure 10.34 *Evapotranspiration and salt balance together ensure that the drainage water from irrigated fields is much saltier than the irrigation water applied. In this example, the irrigation water contains 250 mg salts per liter. Some 75% of the applied water is lost to the atmosphere by evapotranspiration. About 25% of the water applied is used for drainage, which is necessary to maintain the salt balance (prevent the buildup of salts) in the field. The added salts are leached away with the drainage water, which then contains the same amount of salt as was added, but in only 25% of the added amount of water. The concentration of salt in the drainage water is thereby four times as great (1000 mg/L) as in the irrigation water. Disposal and/or reuse of the highly saline drainage water present challenges for any irrigation project.* (Diagram courtesy of Ray R. Weil)

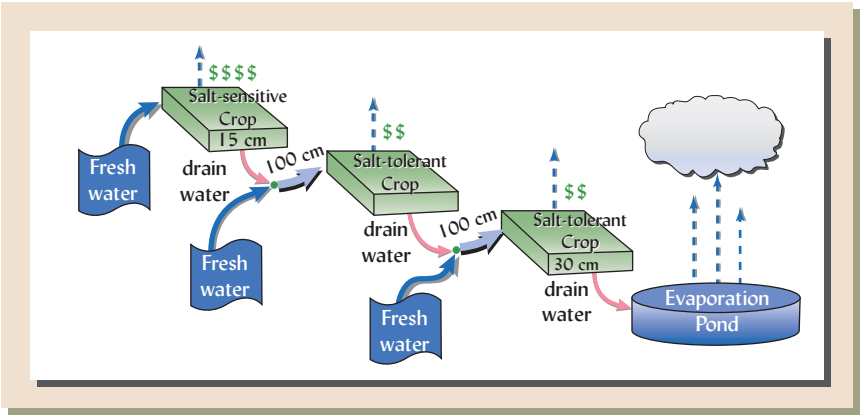

Figure 10.35 *Generalized scheme for recycling irrigation drainage water by mixing it with fresh water and irrigating salt-tolerant crops.* [Redrawn from Letey et al. (2003)]

The Colorado River provides one example of the regional impacts of irrigation systems. By the time this river reaches the U.S.-Mexico border, it is so loaded with salts from upstream irrigation systems and from domestic and industrial uses that a huge desalinization plant has been constructed to enable the United States to meet its treaty obligations with Mexico.

Toxic Elements in Drainage Water. If either the irrigation water or the soil of the irrigated fields contains significant quantities of certain toxic trace elements, these too will become increasingly concentrated in the drainage water. The elements of concern include molybdenum (Mo), arsenic (As), boron (B), and selenium (Se). Molybdenum and selenium are necessary nutrients for animals and humans in trace amounts, but all four elements can be toxic to cattle, wildlife, or people if they become concentrated in water or food. At some locations in the western United States, such trace elements have accumulated to toxic levels in downstream wetlands or evaporative ponds. Table 10.5 shows that plants growing on these affected areas can accumulate levels of these elements that are unsafe for livestock and/or wildlife. Box 10.3 illustrates how toxic concentrations of Se can develop in an irrigation system and become **biomagnified** up the wildlife food chain, as small fish eat water plants and birds eat the fish, etc. The chemistry and cycling of selenium and other trace elements are discussed further in Chapter 15.

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Table 10.5
LEVELS OF MOLYBDENUM AND SELENIUM IN THREE SALINITY-TOLERANT FORAGE SPECIES GROWN ON A HIGHLY SALINIZED SOIL THAT HAD RECEIVED LARGE QUANTITIES OF WASTE IRRIGATION WATER IN THE SAN JOAQUIN VALLEY OF CALIFORNIA, USA
The upper "safe" limit for animal consumption (potential toxicity level) is also shown.

		Level in the forages, mg/kg		
Trace elements	Potential toxicity level, mg/kg	Tall wheatgrass	Alkali sacaton	Astragalus racemosus
Molybdenum	5	26	10	18
Selenium	5	12	9	670

Data selected from Retana et al. (1993).

10.9 RECLAMATION OF SALINE SOILS

The restoration of soil chemical and physical properties conducive to high productivity is referred to as soil ***reclamation***. Reclamation of saline soils is largely dependent on the provision of effective drainage and the availability of good-quality irrigation water (see Table 10.4) so that salts can be leached from the soil. In areas where irrigation water is not available, such as in saline seeps in nonirrigated dry regions, the leaching of salts may not be practical. In these areas, deep-rooted vegetation may be used to lower the water table and reduce the upward movement of salts.

If the natural soil drainage is inadequate to accommodate the leaching water, an artificial drainage network must be installed. Intermittent applications of excess irrigation water may be required to effectively reduce the salt content to a desired level. The process can be monitored by measuring the soil's EC, using either the saturation extract procedure or one of the field instruments described in Section 10.4.

Leaching Requirement (LR)

The amount of water needed to remove the excess salts from saline soils, called the ***LR***, is determined by the characteristics of the crop to be grown, the irrigation water, and the soil. As demonstrated in Box 10.4, an approximation of the *LR* is given for relatively uniform salinity conditions by the ratio of the salinity of the irrigation water (expressed as its EC_{iw}) to the maximum acceptable salinity of the soil solution for the crop to be grown (expressed as EC_{dw}, the EC of the drainage water)

$$LR = \frac{EC_{iw}}{EC_{dw}} \tag{10.9}$$

The *LR* indicates the water that should be added in excess of that needed to thoroughly wet the soil and meet the crop's evapotranspiration needs. Note that if EC_{iw} is high and a salt-sensitive crop is chosen (dictating a low EC_{dw}), a very large leaching requirement *LR* will result. As mentioned in Section 10.8, disposal of the drainage water that has leached through the soil can present a major problem. Therefore, it is generally desirable to use management techniques that minimize the *LR* and the amount of drainage water that requires disposal.

Management of Soil Salinity

Management of irrigated soils should aim to simultaneously minimize drainage water and protect the root zone (usually the upper meter of soil) from damaging levels of salt accumulation. These two goals are obviously in conflict. The irrigator can attempt to find the best compromise between the two and can use certain management techniques that allow plants to tolerate the presence of higher salt levels in the soil profile. One option is to plant

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BOX 10.3

SELENIUM IN IRRIGATED SOILS[a]

The use of selenium-laden irrigation waters can result in the buildup of selenium (Se) to toxic levels in soils and in irrigation wastewaters coming from these soils. Selenium accumulates in plants growing on these soils and in nearby wetland areas where irrigation wastewaters are disposed.

Certain soil parent materials are high in selenium. Under alkaline and aerated soil conditions, the selenate (SeO_4^{2-}) form of selenium prevails. Much like sulfates, selenates are relatively water-soluble and are readily available for plant uptake. They may accumulate in rangeland plants to levels toxic for grazing animals. Or they may be leached from the soil and substrata into the streams draining the watershed. Downstream, the high-Se water in these streams may be used for irrigation.

Figure 10.36 illustrates how return of Se-laden irrigation wastewater to streams for reuse can cause serious environmental problems. Streams from high-Se watersheds provide water for irrigated field A. The Se level in the water (shown by the darkness of the shading in the drainage) is significant, but not sufficient to cause environmental problems.

As with other salts, the Se accumulates in the soil and concentrates in the waste drainage water coming from the soil. This drainage water moves (or is pumped) back into a stream that later supplies water for irrigated field B downstream. The process is repeated, Se in the soil is increased, and the Se level in the drainage water is increased (darker shading). After several such cycles, the concentration of Se (and possibly of other salts) is high enough to make the water unusable for further irrigation. The water is then diverted into wetlands or shallow holding ponds, such as those established in the Kesterson National Wildlife Refuge in California, USA. Birds and other wildlife find these wetlands inviting places to live and breed.

As the water evaporates, the Se concentrates in the remaining water, often exceeding U.S. Environmental Protection Agency (USEPA) criterion of 5 μg Se/L for protection of aquatic life. The Se also moves into the soils of the holding area. Plants living in the area absorb the Se, accumulating it to levels that are toxic to animal life. Indeed, just two years after irrigation wastewater began to flow into holding ponds established in California's Kesterson National Wildlife Refuge, scientists there began to observe widespread death and deformities among wildfowl, mammals, and amphibians that lived in or near the ponds. Selenium poisoning was determined to be responsible for the deformed and dead chicks that were found in some 40% of monitored bird nests at Kesterson.

Steps can be taken to reduce or eliminate the release of high-Se waters into wetlands at Kesterson and elsewhere. Researchers are also seeking plants that are very high Se accumulators so that Se can be removed from holding areas by harvesting the plant biomass. Other research shows that certain bacteria form volatile organic Se compounds, which may be slowly released into the atmosphere in harmless concentrations. The impacts of irrigation on wildlife remind us of the interconnectedness of all parts of the environment and the need to manage soil and water resources with a holistic view of their roles in the larger ecosystem.

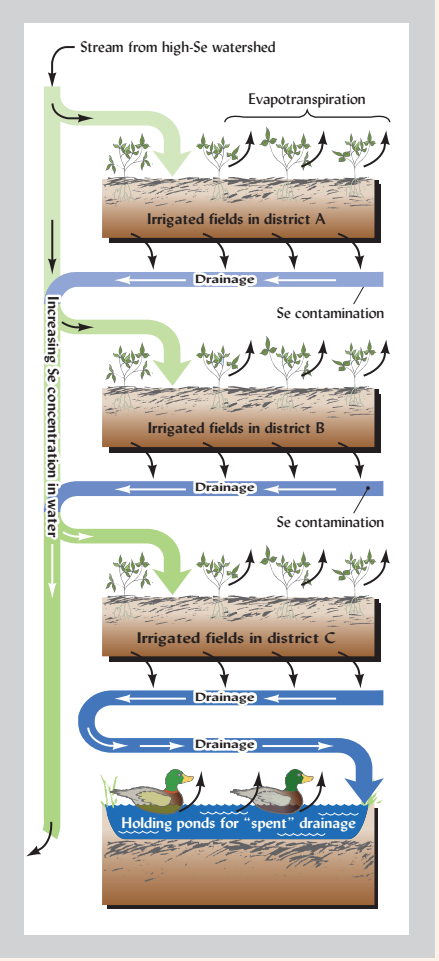

Figure 10.36 *Concentrating Se in an irrigation project.* (Diagram and photo courtesy of Ray R. Weil)

[a]For efforts on reduction of Se pollution, see Banuelos et al. (1997) and Selenium Management Program Workgroup (2011).

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BOX 10.4

LEACHING REQUIREMENT FOR SALINE SOILS

The salt balance in a field can be described by equating the salt inputs and outputs:

$$\underbrace{S_{iw} + S_p + S_f + S_m}_{\text{Salt inputs}} = \underbrace{S_{dw} + S_{dw} + S_c + S_{ppt}}_{\text{Salt outputs}} \quad (10.10)$$

The salt inputs include those from irrigation water (S_{iw}), atmospheric deposition (S_p), fertilizers (S_f), and the weathering or dissolution of existing soil minerals (S_m). The salt outputs are due to drainage water (S_{dw}), crop removal (S_c), and chemical precipitation (S_{ppt}) of carbonates and sulfates. Usually S_{iw} and S_{dw} are far larger than the other terms in Eq. (10.10), so the main concern is to balance the salt coming in with the irrigation water and that leaving with the drainage water:

$$\underbrace{S_{iw}}_{\text{Salt in with irrigation water}} = \underbrace{S_{dw}}_{\text{Salt out with drainage water}} \quad (10.11)$$

We can estimate the quantity of salt S carried in drainage or irrigation as the product of the volume of the water (expressed as cm depth applied to an area of land) and the concentration of salt in that water (as approximated by its EC). Therefore, we can rewrite Eq. (10.11) as follows (using the same subscripts as before):

$$D_{iw} \times EC_{dw} = D_{dw} \times EC_{dw} \quad (10.12)$$

Rearranging the terms, we obtain the following expression that defines the LR or the ratio of drainage water depth to irrigation water depth (D_{dw}/D_{iw}) needed to maintain salt balance:

$$\frac{EC_{iw}}{EC_{dw}} = \frac{D_{dw}}{D_{iw}} = LR \quad (10.13)$$

The LR tells farmers how much irrigation water (in excess of that required to wet the soil) they should apply for sufficient leaching. The goal is usually to assure that the upper two-thirds of the root zone does not accumulate salts beyond the level acceptable for a particular crop.

From Eq. (10.13), we see that LR also equals the ratio of the irrigation water EC to the drainage water EC:

$$LR = \frac{EC_{iw}}{EC_{dw}} \quad (10.9)$$

where EC_{dw} is an acceptable level for the crop being grown. What is considered an acceptable EC_{dw} is open to interpretation. An acceptable EC_{dw} might be interpreted to mean the EC_e that allows 90% of maximum crop yield. A more conservative interpretation of acceptable EC_{dw} is the threshold EC_e at which the growth of the particular crop just begins to decline (usually 1–2 dS/m lower than that which gives the 90% yield level).

As an example, consider the situation where the irrigation water has an EC_{iw} of 2.5 dS/m and a moderately tolerant crop (e.g., broccoli) is to be grown. If information that is more specific is unavailable, the acceptable EC_{dw} for the crop can be (roughly) estimated from the column heading in Table 10.3. For a moderately tolerant crop, we can use 8 dS/m as the acceptable EC_{dw} to produce 90% of the maximum yield. Then,

$$LR = \frac{2.5\ \text{dS/m}}{8\ \text{dS/m}} = 0.31 \quad (10.14)$$

If this LR (0.31) is multiplied by the amount of water needed to wet the root zone—let us suppose it is 12 cm of water—the amount of water to be leached would be 3.7 cm (12 cm $\times$ 0.31). This is the minimum amount of water that must be leached through a water-saturated soil to maintain the root zone salinity at the acceptable level. A more sensitive crop could be grown in this soil, but it would have a lower acceptable EC_{dw} and therefore would require the application of a greater amount of water for leaching.

salt-tolerant species or choose the most salt-tolerant varieties within a crop species (as discussed in Section 10.7).

Irrigation Timing. The timing of irrigation is extremely important on saline soils, particularly early in the growing season. Germinating seeds and young seedlings are especially sensitive to salts. Therefore, irrigation should precede or immediately follow planting to move the salts downward and away from the seedling roots. The irrigator can use high-quality water to keep root-zone salinity low during the sensitive early growth stages and then switch to lower-quality water as the maturing plants become more salt-tolerant.

Location of Salts in the Root Zone. Tillage and planting practices can influence the location and accumulation of salts in arid-region soils. Tillage or surface-residue management practices (such as mulches or conservation tillage) that reduce evaporation from the soil surface should also reduce the upward transport of soluble salts. Likewise, specific techniques

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for applying irrigation water that direct salt concentrations away from young plant roots can allow higher levels of salt to accumulate without damage to the crop. Applying water in every other furrow and asymmetrically planting only on the wet side of the furrows can provide significant protection to young plants (Figure 10.37).

Frequent application of water, as with sprinkler- or drip-irrigation systems (see Section 6.9), can help move salts away from plant roots. Proper placement of water emitters in drip-irrigation systems is crucial in establishing a low-salt zone around sensitive young plants. Buried drip-emitter lines, in particular, can cause problems by moving salts to the soil surface where seeds are germinating (Figure 10.37*e*). The water emitted below the surface moves toward the soil surface by capillary rise, carrying dissolved salts with it. When the water evaporates or is taken up by plant roots, the salts are left to concentrate at the soil surface. The size and shape of the low-salinity zone created by drip irrigation is also dependent on the rate of water application and the texture of the soil (Figure 10.38).

Spatial Variability. The actual leaching fraction applied to a field may exceed the theoretical amount calculated from the *LR* if soil salinity levels vary from spot to spot in a field. In order to avoid yield losses from salinity, a farmer may irrigate a field with the amount of water determined by the *LR* of the *most saline* parts of the field. This amount will assure that the most saline parts of the field are properly leached, but it will waste valuable water and create more than the necessary amount of drainage water in the less saline parts of the field.

It may be feasible to avoid such inefficiencies by using *precision agriculture* technology. For example, irrigation systems (such as sprinkler or drip) could be designed with variable rate controls and used in conjunction with soil-salinity sensing devices (such as the multielectrode probe or the electromagnetic induction sensor described in Section 10.4) so that they apply just the right amount of leaching water for each part of a field.

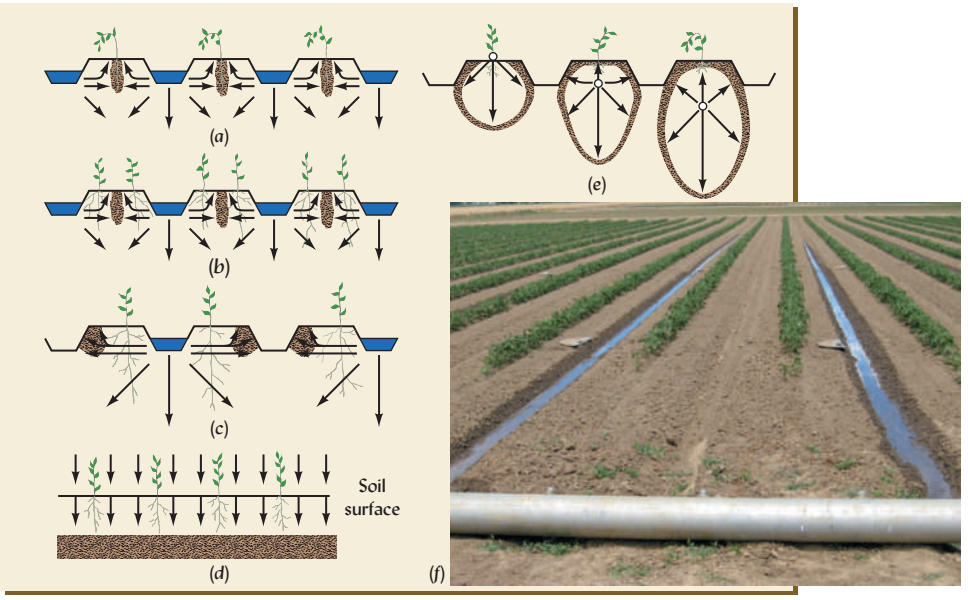

Figure 10.37 *Effect of irrigation techniques on salt movement and plant growth in saline soils. (a) With irrigation water applied to furrows on both sides of the row, salts move to the center of the ridge and damage young plants. (b) Plants on the edges of the bed avoid the most concentrated salts. (c) Application of water to every other furrow and placement of plants near the water helps plants avoid highest salt concentrations. (d) Sprinkler irrigation or uniform flooding temporarily moves salts downward out of the root zone, but the salts will return as the soil surface dries out and water moves up by capillary flow. (e) Drip irrigation at low rates provides a nearly continuous flow of water, creating a low-salt soil zone with the salts concentrated at the wetting front. The placement of the drip emitters largely determines whether the salts are moved toward or away from the plant roots. (f) An example of alternate furrow irrigation in California, USA, but with tomatoes planted in the center, rather than along the irrigated furrow side of the beds where salts are lowest.* [Diagram courtesy of Wesley M. Jarrell; photo courtesy of Guihua Chen]

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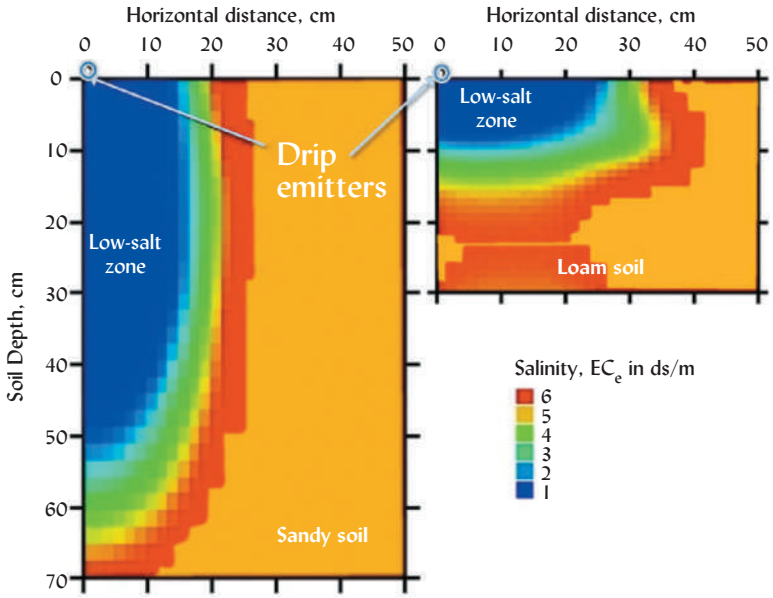

Figure 10.38 *Effect of soil texture on distribution of salts after irrigation from surface drip emitters. The salts were originally distributed evenly within each soil, but the slowly applied irrigation water (4 L/h for 3 hours) dissolved the salts and moved them away from the emitters toward the border between the wet and dry soil (the wetting front). Note that the low-salt zone in the sandy soil is much deeper, but more narrow, than in the loam. Repeated irrigation at short intervals may keep the salts away from the root zone. However, if the soil is allowed to dry, the dissolved salts will begin to return to the root zone as the matric potential gradient draws water toward the drier soil.*
[Redrawn from data in Bresler (1975)]

Some Limitations of the Leaching Requirement Approach[9]

The leaching requirement approach to managing irrigated soils is only an approximation and has several inherent weaknesses. First, additional leaching may be needed, in some cases, to reduce the excess concentration of specific elements, such as boron. Second, the *LR* by itself does not take into account the rise in the water table that is likely to result from increased leaching, and so it may lead to waterlogging and, eventually, increased salinization. Third, irrigation using a simple *LR* approach usually overapplies water because an entire field is treated to avoid salt damage in its most saline spots. Fourth, the *LR* method does not consider salts that may be picked up from fossil salt deposits already in the soil and substrata. Fifth, it assumes that the EC of the drainage water is known, but in fact this may be largely unknown, since it may take years or even decades for the water applied in irrigation to reach the main drains where it can be easily sampled. In other words, the drainage water sampled today may represent the leaching conditions of several months or years ago.

An alternative approach would be to closely monitor the salinity in the soil profile by taking repeated measurements across the field, using the EM sensor or four-electrode methods discussed in Section 10.4. The sufficiency of leaching and the dominant direction of water movement could then be judged from the type of salinity profile observed (Figure 10.39). This more complex approach, combined with site-specific management techniques, seems to hold promise for more efficient management and reclamation of salt-affected soils under irrigation.

10.10 RECLAMATION OF SALINE–SODIC AND SODIC SOILS

Saline–sodic soils have some of the adverse properties of both saline and sodic soils. If attempts are made to leach out the soluble salts in saline–sodic soils, as was discussed for saline soils, the exchangeable Na^+ level as well as the pH would likely increase, and the soil would take on adverse characteristics of sodic soils. Consequently, for both saline–sodic and sodic soils, attention must first be given to reducing the level of exchangeable Na^+ ions and then to the problem of excess soluble salts.

[9]For a discussion of how detailed spatial assessment of salinity can be used as an alternative to the *LR* approach, see Rhoades et al. (1999) and Corwin and Lesch (2013).

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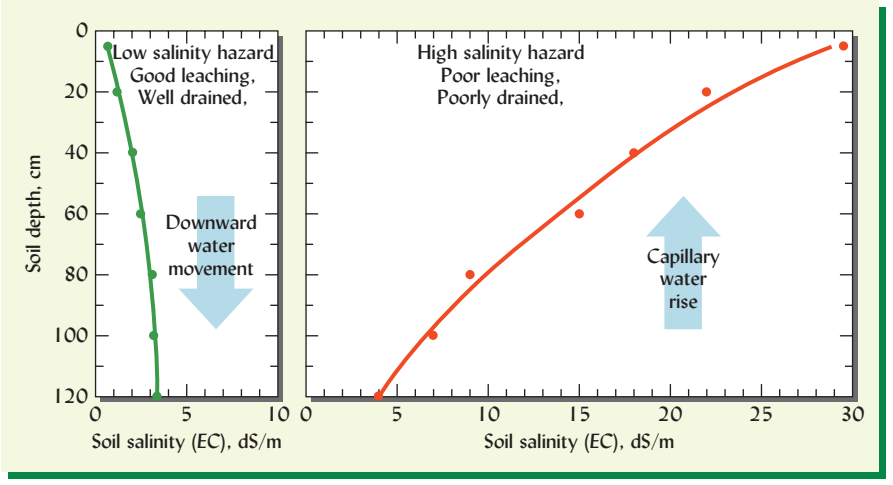

Figure 10.39 *Soil salinity profile curves show the levels of salts throughout the root zone. The shapes of the curves also indicate whether leaching has been sufficient and whether saline water is rising from a shallow water table. The arrows indicate the direction of water flow for the low- and high-salinity soils. The curve on the right shows increasing salinity near the soil surface, a pattern that is typical of saline seeps and waterlogged irrigated fields. Note that the leftmost curve is similar in shape to the salinity profile of a dry, well-drained soil under desert pavement in which there is no influence of groundwater (compare to Figure 10.4,* left*).* (Diagram courtesy of Ray R. Weil)

Gypsum

Removing Na^+ ions from the exchange complex is most effectively accomplished by replacing them with either the Ca^{2+} or the H^+ ion. Providing Ca^{2+} in the form of gypsum ($CaSO_4 \cdot 2H_2O$) is the most practical way to bring about this exchange. The relatively high solubility of gypsum will also increase the ionic strength, thus further helping to flocculate the soil. When gypsum is added, reactions such as the following take place:

$$2NaHCO_3 + CaSO_4 \rightarrow CaCO_3 + \underset{\text{(leachable)}}{Na_2SO_4} + CO_2\uparrow + H_2O \tag{10.15}$$

$$Na_2CO_3 + CaSO_4 \rightleftharpoons \underset{\text{(insoluble)}}{CaCO_3} + \underset{\text{(leachable)}}{Na_2SO_4} \tag{10.16}$$

$$\begin{matrix} Na^+ \\ Na^+ \end{matrix}\boxed{\text{Colloid}} + CaSO_4 \rightleftharpoons Ca^{2+}\boxed{\text{Colloid}} + Na_2SO_4 \tag{10.17}$$

Note that in each case the soluble salt Na_2SO_4 is formed, which can be easily leached from the soil as was done in the case of the saline soils.

Several tons of gypsum per hectare are usually necessary to achieve reclamation. In Box 10.5, calculations are made to approximate the amount of gypsum that is theoretically needed to remove an acceptable portion of the Na^+ ion from the exchange complex. The soil must be kept moist to hasten the reaction, and the gypsum should be thoroughly mixed into the surface by cultivation—not simply plowed under. The treatment must be supplemented later by a thorough leaching of the soil with irrigation water to leach out most of the sodium sulfate.

Gypsum is inexpensive, widely available in both natural and in industrial by-product forms, and easily handled. Care must be taken, however, to be certain that the gypsum is finely ground and that it is well mixed with the upper soil horizons so that its solubility and rate of reaction are maximized.

Sulfur and Sulfuric Acid

Elemental sulfur and sulfuric acid can be used to advantage on sodic soils, especially where sodium bicarbonate abounds. The sulfur, upon biological oxidation (see Sections 9.6 and 13.19), yields sulfuric acid, which not only changes the sodium bicarbonate to the less harmful and more leachable sodium sulfate but also decreases the pH. The reactions of sulfuric acid with the compounds containing sodium may be shown as follows:

$$2NaHCO_3 + H_2SO_4 \rightarrow 2CO_2\uparrow + 2H_2O + \underset{\text{(leachable)}}{Na_2SO_4} \tag{10.18}$$

$$Na_2CO_3 + H_2SO_4 \rightarrow CO_2\uparrow + H_2O + \underset{\text{(leachable)}}{Na_2SO_4} \tag{10.19}$$

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BOX 10.5

CALCULATING THE THEORETICAL GYPSUM REQUIREMENT

PROBLEM

How much gypsum is needed to reclaim a sodic soil with an ESP of 25% and a cation exchange capacity of 18 $cmol_c$/kg? Assume that you want to reduce the ESP of the upper 30 cm of soil to about 5% so that a crop like alfalfa could be grown.

SOLUTION

First, determine the amount of Na^+ ions to be replaced by multiplying the CEC (18) by the change in Na^+ saturation desired (25 − 5 = 20%).

$$18\ cmol_c/kg \times 0.20 = 3.6\ cmol_c/kg$$

From the reaction that occurs when the gypsum ($CaSO_4 \cdot 2H_2O$) is applied,

$$\boxed{\text{Colloid}}\begin{matrix}Na^+\\Na^+\end{matrix} + CaSO_4 \cdot 2H_2O \rightleftharpoons \boxed{\text{Colloid}}\ Ca^{2+} + Na_2SO_4 + 2H_2O \qquad (10.21)$$

We know that the Na^+ is replaced by a chemically equivalent amount of Ca^{2+} in the gypsum ($CaSO_4 \cdot 2H_2O$). In other words, 3.6 $cmol_c$ of $CaSO_4 \cdot 2H_2O$ will be needed to replace 3.6 $cmol_c$ of Na^+.

Second, calculate the weight in grams of gypsum needed to provide the 3.6 $cmol_c$/kg soil. This can be done by first dividing the molecular weight of $CaSO_4 \cdot 2H_2O$ (172) by 2 (since Ca^{2+} has two charges and Na^+ only one) and then by 100 since we are dealing with centimolec rather than $mole_c$

$$\frac{172}{2} = 86\ g\ CaSO_4 \cdot 2H_2O/mol_c$$

and $\frac{86}{100} = 0.86$ g $CaSO_4 \cdot 2H_2O/cmol_c$ required to replace 1 $cmol_c$ Na^+

The 3.6 $cmol_c Na^+$/kg would require

$$3.6\ cmol_c/kg \times 0.86/cmol_c = 3.1\ g\ CaSO_4 \cdot 2H_2O/kg\ of\ soil$$

Last, to express this in terms of the amount of gypsum needed to treat 1 ha of soil to a depth of 30 cm, multiply by 4×10^6, which is twice the weight in kg of a 15-cm-deep hectare–furrow slice (see Section 4.7, footnote 11)

$$3.1\ g/kg \times 4 \times 10^6\ kg/ha = 12{,}400{,}000\ g\ gypsum/ha$$

This is 12,400 kg/ha, 12.4 Mg/ha (or about 5.5 English tons/acre).

Because of impurities in the gypsum and the inefficiency of the overall process, these amounts would likely be adjusted upward by 20–30% in actual field practice to account for less than complete reactivity. However, if the soil in question naturally contains some gypsum, that amount should be subtracted from the total just calculated. Finally, it is advisable to apply only half of the recommended amount at one time, with the remaining half applied about six months later, if necessary.

$$\begin{matrix}Na^+\\Na^+\end{matrix}\boxed{\text{Colloid}} + H_2SO_4 \rightleftharpoons \begin{matrix}H^+\\H^+\end{matrix}\boxed{\text{Colloid}} + \underset{\text{(leachable)}}{Na_2SO_4} \qquad (10.20)$$

Not only are the sodium carbonate and bicarbonate changed to sodium sulfate, a mild neutral salt, but the carbonate anion is removed from the system. When gypsum is used, however, a portion of the carbonate may remain as a calcium compound ($CaCO_3$).

In research trials, sulfur and even sulfuric acid have proven to be very effective in the reclamation of sodic soils, especially if large amounts of $CaCO_3$ are present. In practice, however, gypsum is much more widely used than the acid-forming materials.

Physical Condition

The effects of gypsum and sulfur on the physical condition of sodic soils is perhaps more spectacular than are the chemical effects. Sodic soils are almost impermeable to water, since the soil colloids are largely dispersed and the soil is essentially void of stable aggregates (see Table 10.6). When the exchangeable Na^+ ions are replaced by Ca^{2+} or H^+, soil aggregation and improved water infiltration results (Figure 10.40). The neutral sodium salts (e.g., Na_2SO_4) formed when the exchange takes place can then be leached from the soil, thereby reducing both salinity and sodicity. Some research suggests that aggregate-stabilizing synthetic polymers may be helpful

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Table 10.6
THE DEGREE OF AGGREGATION OF TWO SALT-AFFECTED ALFISOLS (XERALFS) AFTER REPEATED WETTING (EIGHT TIMES) WITH SOLUTIONS DIFFERING IN SODIUM AND CALCIUM CONTENTS
The Na treatment simulates irrigation water with high SAR. The addition of gypsum is simulated by the Ca treatment. Note that in each case the Na treatment reduced aggregation and the Ca treatment increased it.

Soil	Aggregate size, μm	Original, %	Na-treated, %	Ca-treated, %
Farrell	>50	5.1	3.1	9.9
	20–50	12.8	2.1	18.0
Tarlee	>50	15.6	0.0	34.1
	20–50	11.2	5.4	42.0

From Barzegar et al. (1996).

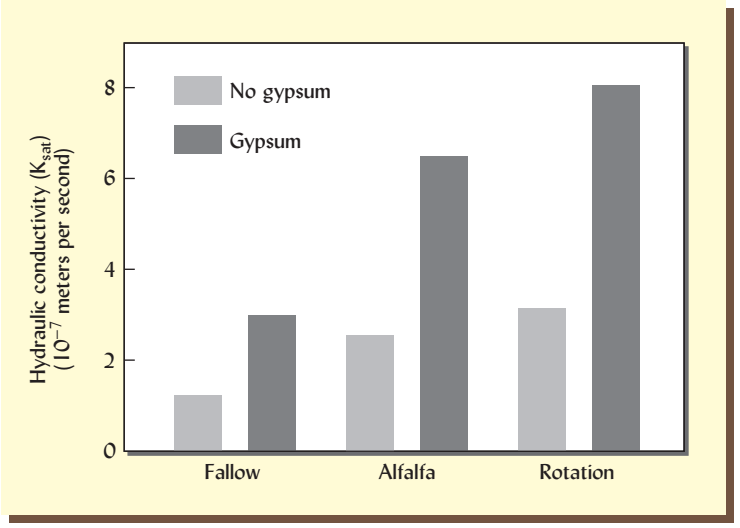

Figure 10.40 *The influence of gypsum and growing crops on the hydraulic conductivity (K_{sat}) of the upper 20 cm of a saline–sodic soil (Natrustalf) in Pakistan. The use of gypsum to increase water conductivity in all plots was more effective when deep-rooted alfalfa and rotation of sesbania-wheat were grown.* [Drawn from selected data from Ilyas et al. (1993); used with permission of the Soil Science Society of America]

in at least temporarily increasing the water infiltration capacity of gypsum-treated sodic soils. Data in Table 10.7 from one experiment show the possible potential of these soil conditioners, especially when used in combination with gypsum.

Deep-Rooted Vegetation. The reclamation effects of gypsum or sulfur are greatly accelerated by plants growing on the soil. Crops that have some degree of tolerance to saline and sodic soils, such as sugar beets, cotton, barley, sorghum, berseem clover, or rye, can be grown initially. Their roots help provide channels through which gypsum can move downward into the soil. Deep-rooted crops, such as alfalfa, are especially effective in improving the water conductivity of gypsum-treated sodic soils. Figure 10.40 illustrates the ameliorating effects of the combination of gypsum and deep-rooted crops.

Air Injection. In addition to reduced diffusion of air because of soil dispersion, irrigated soils may provide less than optimal oxygen availability to roots because irrigation water—especially applied by drip systems—contains much less dissolved oxygen than rainwater. One approach to improving the aeration of the root zone in heavy-textured, irrigated soils is to mechanically add air. This can be easily accomplished by injecting air into drip irrigation lines (Figure 10.41) and may be practical for high-value crops and ornamental landscape containers.

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Table 10.7
USE OF GYPSUM AND SYNTHETIC POLYMERS ON RECLAMATION OF A SODIC SOIL
Adding gypsum to samples of a fine-textured (clay) saline–sodic soil, a Mollisol from California, USA, increased both the hydraulic conductivity and the salts leached in the experiment while decreasing the exchangeable sodium percentage (ESP). Adding two experimental synthetic polymers (T4141 and 21J) with the gypsum gave even greater increases in hydraulic conductivity and leached salts.

	Characteristic measured					
	Hydraulic conductivity, mm/h		Total salts leached, mg/kg		ESP, %	
Gypsum added? →	No	Yes	No	Yes	No	Yes
Polymer treatment						
No polymer	0.0	0.06	0.0	4.7	22.9	9.6
T4141	0.0	0.28	0.0	10.1	25.4	9.6
21J	0.0	0.28	0.0	9.7	25.5	9.6

Data from Zahow and Amrhein (1992).

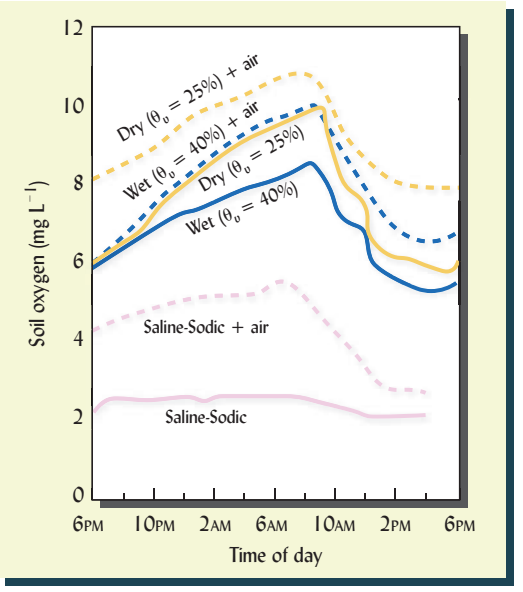

Figure 10.41 *Soil oxygen content in normal and saline–sodic soils as affected by adding air to water supplied by buried drip irrigation emitters. Mature tomato plants were grown in large pots filled with heavy clay soil (a Vertisol) and either kept wet ($\theta_v = 40\%$ water, near field capacity) or dry ($\theta_v = 25\%$ water). In the normal soil, adding air (dotted lines) to wet soil achieved the same O_2 level as in the drier soil. Saline–sodic conditions were created by applying enough NaCl to raise the EC_e to 8.8 dS/m. Under these conditions, soil dispersion impeded air movement causing low O_2 levels even when air was added. Note that for all treatments, the O_2 levels declined during the day when plant roots are most actively respiring and taking up water and nutrients. Air was added into the drip lines by a venturi inlet and O_2 was measured by fiber-optic mini-sensors located at 15 cm depth from the soil surface.* [Drawn from data in Bhattarai et al. (2006)]

Ammonia Effects

The practice in recent years of adding nitrogen as anhydrous ammonia (NH_3) to irrigation water as it is applied to a field has created some soil problems. The NH_3 reacts with the irrigation water to form NH_4OH

$$NH_3 + H_2O \rightarrow NH_4OH \tag{10.22}$$

The high pH brought about by this reaction causes the precipitation of calcium and magnesium carbonates, as indicated by downward arrows

$$Ca(HCO_3)_2 + 2NH_4OH \rightarrow CaCO_3\downarrow + (NH_4)_2CO_3 + 2H_2O \tag{10.23}$$

$$Mg(HCO_3)_2 + 2NH_4OH \rightarrow MgCO_3\downarrow + (NH_4)_2CO_3 + 2H_2O \tag{10.24}$$

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This removal of the Ca^{2+} and Mg^{2+} ions from the irrigation water raises the SAR and the hazard of increased ESP. To counteract these difficulties, sulfuric acid is sometimes added to the irrigation water to reduce its pH as well as that of the soil. This practice may well spread where there are economical sources of sulfuric acid and where the personnel applying it have been trained and alerted to the serious hazards of using this strong acid.

10.11 MANAGEMENT OF RECLAIMED SOILS

Once salt-affected soils have been reclaimed, prudent management steps must be taken to be certain that the soils remain productive. For example, surveillance of the EC and SAR and trace element composition of the irrigation water is essential. Management adjustment is needed to accommodate any change in water quality that could affect the soil. The number and timing of irrigation episodes helps determine the balance of salts entering and leaving the soil. Likewise, the maintenance of good internal drainage is essential for the removal of excess salts.

Steps should also be taken to monitor appropriate chemical characteristics of the soils, such as pH, EC, and SAR, as well as specific levels of such elements as boron, chlorine, molybdenum, and selenium that could lead to chemical toxicities. These measurements will help determine the need for subsequent remedial practices and/or chemicals.

Crop and soil fertility management for satisfactory yield levels is essential to maintain the overall quality of salt-affected soils. The crop residues (roots and aboveground stalks) will help maintain organic matter levels and good physical condition of the soil. To maintain high yields, micronutrient and phosphorus deficiencies characteristic of other high-pH soils will need to be overcome by adding appropriate organic and inorganic sources.

10.12 CONCLUSION

Arid and semiarid regions predominantly feature alkaline and salt-affected soils. These soils typically exhibit above-neutral pH values throughout their profiles and often have calcic (calcium carbonate-rich) or gypsic (gypsum-rich) horizons at some depth. Such soils cover vast areas and support important—though water-limited—desert and grassland ecosystems. Soils of dry regions interact with scattered vegetation to influence the hydrology and fertility of the landscapes that are characterized by small "islands of fertility." Among the unique features that play a role in shaping these ecosystems are desert pavement and microbiologic crusts.

People use large areas of these soils for rangeland and dryland farming. In fact, almost half of the world's arable soils are salt-affected or alkaline in nature. Many of these soils are quite well endowed with plant nutrients and, if irrigated, can be among the most productive soils in the world. Irrigation of alkaline soils of arid regions almost inevitably leads to the accumulation of salts, which must be carefully managed.

Since their pH levels are high, management practices used on these soils are quite different from those applied to acid-soil regions. The high-pH, calcium-rich conditions of alkaline soils commonly lead to deficiencies of certain essential micronutrients (especially iron and zinc) and macronutrients (especially phosphorus). In localized areas boron, molybdenum, and selenium may be so readily available as to accumulate in plants to levels that can harm grazing animals.

Scientists have grouped salt-affected soils into three classes based on their total salt content (indicated by EC) and the proportion of sodium among the cations (indicated by either the SAR or the ESP). *Saline soils* are dominated by neutral salts ($EC_e > 4$ dS/m) and by pH values less than 8.5. *Saline–sodic* soils have similar salt and pH levels, but with EPS > 15 and SAR > 13. *Sodic soils* also have the same high levels of sodium, but their soluble salt concentrations are relatively low ($EC_e < 4$ dS/m), and their pH values are higher than 8.5. The physical conditions of saline and saline–sodic soils are satisfactory for plant growth, but the colloids in sodic soils are largely dispersed, the soil is puddled and poorly aerated, and the water infiltration rate is extremely slow.

If irrigators in arid regions apply only enough water to meet plant evapotranspiration needs, salts will build up relentlessly in the soil until the land becomes too salinized to grow crops. Therefore, just as the humid-region farmer must be ever on guard to counteract acidification, so the arid-region irrigator must be ever vigilant to combat salinization. Whereas the humid-region farmer periodically uses lime to restore a favorable balance between H^+ ion consumption and production, the irrigator uses periodic leaching to restore the balance between the import and export of salts.

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Furthermore, there can be no effective leaching if drainage is insufficient to carry away the leaching water. Thus, leaching and drainage are both essential components of any successful irrigation scheme. However, the leaching of salts is not a simple matter, and it inevitably leads to additional problems both in the field being leached and in sites further downstream. At best, salinity management in irrigation agriculture provides a compromise between unavoidable evils.

The reclamation of saline–sodic and sodic soils requires an additional process before leaching of excess salinity can be achieved. In order to make these soils permeable enough for leaching to take place, the excess exchangeable sodium ions must first be removed from the exchange complex. This is accomplished by replacing the Na^+ ions with either Ca^{2+} or H^+ ions. The Ca^{2+} or H^+ ions then stimulate flocculation and increased permeability to the point that the replaced sodium and other salts can be leached downward and out of the profile. Gypsum ($CaSO_4 \cdot 2H_2O$) and elemental sulfur (S) are two amendments that can supply the Ca^{2+} and H^+ ions needed. Monitoring the chemical content of both the irrigation water and the soil is essential to achieve this goal of removing the Na^+ ions from the exchange complex and, ultimately, the soil.

About 20% of the world's farmland is irrigated, up from only 10% in 1960. Impressively, this land produces some 45% of our food supply. The world increasingly depends on irrigated agriculture in dry regions for the production of food for its growing population. Unfortunately, irrigated agriculture is in inherent disharmony with the nature of arid-region ecology. We have seen that it is therefore fraught with difficulties that require constant and careful management if human and environmental tragedies are to be avoided.

STUDY QUESTIONS

1. What are the primary sources of alkalinity in soils? Explain.
2. Compare the availability of the following essential elements in alkaline soils with that in acid soils: (1) iron, (2) nitrogen, (3) molybdenum, and (4) phosphorus.
3. The iron analysis of an arid-region soil showed an abundance of this element, yet a peach crop growing on the soil showed serious iron deficiency symptoms. What is a likely explanation?
4. A soil with an abundance of $CaCO_3$ may have a pH no higher than about 8.3, while a nearby soil with high Na_2CO_3 content has a pH of 10.5. What is the primary reason for this difference?
5. An arid-region soil, when it was first cleared for cropping, had a pH of about 8.0. After several years of irrigation, the crop yield began to decline, the soil aggregation tended to break down, and the pH had risen to 10. What is the likely explanation for this situation?
6. What physical and chemical treatments would you suggest to bring the soil described in question 5 back to its original state of productivity?
7. You receive a lab analysis (as shown in the accompanying table) of the exchangeable cations in alkaline soils from four sites you are managing. Calculate the CEC of the soil and the exchangeable sodium percentage (ESP) for each soil:

	Exch. cation concentration, $cmol_c\ kg^{-1}$					
Site I.D.	Na	K	Ca	Mg	CEC	ESP
A	1	1.2	3	3		
B	1	1.2	17.4	6		
C	4.3	1.2	3	3		

8. In your position as consultant you receive the data in the accompanying table for the soil water extracted from three soils under your management. Calculate the SAR and the CROSS for each soil.

	Concentrations of cations, $mg\ L^{-1}$					
Soil I.D.	Na	K	Ca	Mg	SAR	CROSS
A	230	46	40	24		
B	230	46	230	48		
C	990	46	40	24		

9. What are some of the adverse consequences of using wetlands as recipients of irrigation wastewater?
10. Using the information in Table 10.2 and assuming only Na^+ and Ca^{2+} are present and the SAR, calculate the TDS (mg/L) and EC_w of the solution represented by 10 $mmol_c\ L^{-1}$ on the x-axis scale in Figure 10.25.
11. Calculate the leaching requirement to prevent the buildup of salts in the upper 45 cm of a soil if the EC_{dw} of the drainage water is 6 dS/m and the EC_{iw} of the irrigation water is 1.2 dS/m.
12. What are the advantages of using gypsum ($CaSO_4 \cdot 2H_2O$) in the reclamation of a sodic soil? Show the chemical reactions that take place.
13. Calculate the quantity of gypsum needed to reclaim a sodic soil (EPS = 30%) when CEC = 25 $cmol_c$/kg and pH is 10.2. Assume you want an ESP no higher than 4%.

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REFERENCES

Abrol, I. P., J. S. P. Yadov, and F. I. Massoud. 1988. "Salt-affected soils and their management." *FAO Soils Bulletin* 39. Food and Agriculture Organization of the United Nations, Rome. Complete text available at www.fao.org/docrep/x5871e/x5871e00.htm.

Banuelos, G. S., H. A. Ajwa, B. Mackey, L. Wu, C. Cook, S. Akohoue, and S. Zambruzuski. 1997. "Evaluation of different plant species used for phytoremediation of high selenium." *Journal of Environmental Quality* **26**:639–648.

Barzegar, A. R., J. M. Oades, and P. Rengasamy. 1996. "Soil structure degradation and mellowing of compacted soils by saline-sodic solutions." *Soil Science Society of America Journal* **60**:583–588.

Bhattarai, S. P., L. Pendergast, and D. J. Midmore. 2006. "Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils." *Scientia Horticulturae* **108**:278–288.

Bresler, E. 1975. "Two-dimensional transport of solutes during non-steady infiltration from a trickle source." *Soil Science Society of America Proceedings* **39**:604–613.

Corwin, D. L., and S. M. Lesch. 2013. "Protocols and guidelines for field-scale measurement of soil salinity distribution with EC*a*-directed soil sampling." *Journal of Environmental & Engineering Geophysics* **18**:1–25.

Crescimanno, G., M. Iovino, and G. Provenzano. 1995. "Influence of salinity and sodicity on soil structural and hydraulic characteristics." *Soil Science Society of America Journal* **59**:1701–1708.

Dontsova, K. M., and L. D. Norton. 2002. "Clay dispersion, infiltration, and erosion as influenced by exchangeable Ca and Mg." *Soil Science* **167**:184–193.

Evangelou, V. P., and R. E. Phillips. 2005. "Cation exchange in soils." In A. Tabatabai and D. Sparks (eds.). *Chemical Processes in Soils*. SSSA Book Series No. 8. Soil Science Society of America, Madison, WI, pp. 343–410.

FAO. 2013. FAOSTAT [Online]. Food and Agriculture Organization of the United Nations. Available at http://faostat.fao.org/ (verified 20 May 2013).

Gleick, P. H., J. Christian-Smith, and H. Cooley. 2011. "Water-use efficiency and productivity: Rethinking the basin approach." *Water International* **36**:784–798.

Hopkins, D., K. Chambers, A. Fraase, Y. He, K. Larson, L. Malum, L. Sande, J. Schulte, E. Sebesta, D. Strong, E. Viall, and R. Utter. 2012. "Evaluating salinity and sodium levels on soils before drain tile installation: A case study." *Soil Horizons* **53**: 24-29.

Ilyas, M., R. W. Miller, and R. H. Qureski. 1993. "Hydraulic conductivity of saline-sodic soil after gypsum application." *Soil Science Society of America Journal* **57**:1580–1585.

Letey, J. 2000. "Soil salinity poses challenges for sustainable agriculture and wildlife." *California Agriculture* **54**(2):43–48.

Letey, J., D. E. Birkle, W. A. Jury, and I. Kan. 2003. "Model describes sustainable long-term recycling of saline agricultural drainage water." *California Agriculture* **57**:24–27.

Maas, E. V., and S. R. Grattan. 1999. "Crop yields as affected by salinity." In R. W. Skaggs and J. van Schilfgaarde (eds.). *Agricultural Drainage*. Agronomy Monograph No. 38. ASA, CSSA, SSSA, Madison, WI, Chap. 3.

Mace, J. E., and C. Amrhein. 2001. "Leaching and reclamation of a soil irrigated with moderate SAR waters." *Soil Science Society of America Journal* **65**:199–204.

Munns, R. 2002. "Comparative physiology of salt and water stress." *Plant, Cell and Environment* **25**:239–250.

Norton, J. B., J. A. Sandor, and C. S. White. 2007. "Runoff and sediments from hillslope soils within a Native American agroecosystem." *Soil Science Society of America Journal* **71**:476–483.

Rengasamy, P. 2006. "World salinization with emphasis on Australia." *Journal of Experimental Botany* **57**:1017–1023.

Rengasamy, P., and A. Marchuk. 2011. "Cation ratio of soil structural stability (cross)." *Soil Research* **49**:280–285.

Retana, J., D. R. Parker, C. Amrhein, and A. L. Page. 1993. "Growth and trace element concentrations of 5 plant species grown on a highly saline soil." *Journal of Environmental Quality* **22**:805–811.

Rhoades, J. D., F. Chanduvi, and S. Lesch. 1999. *Soil Salinity Assessment Methods and Interpretation of Electrical Conductivity Measurements*. FAO Irrigation and Drainage Paper No. 57. Food and Agriculture Organization of the United Nations, Rome.

Selenium Management Program Workgroup. 2011. Selenium management program. Program Formulation Document Bureau of Reclamation, Gunnison River Basin, CO. http://www.seleniumtaskforce.org/images/Final-SMP-ProgForm.pdf

Szabolcs, I. 1989. *Salt-Affected Soils*. CRC Press, Boca Raton, FL, 274p

Teague, W. R., S. L. Dowhower, S. A. Baker, N. Haile, P. B. DeLaune, and D. M. Conover. 2011. "Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie." *Agriculture, Ecosystems & Environment* **141**:310–322.

Wichelns, D., and M. Qadir. 2015. "Achieving sustainable irrigation requires effective management of salts, soil salinity, and shallow groundwater." *Agricultural Water Management* 157:31–38.

Wood, Y. A., R. C. Graham, and S. G. Wells. 2005. "Surface control of desert pavement pedologic process and landscape function, cima volcanic field, Mojave Desert, California." *CATENA* **59**:205–230.

Yan, N., P. Marschner, W. Cao, C. Zuo, and W. Qin. 2016. "Influence of salinity and water content on soil microorganisms." *International Soil and Water Conservation Research* 4: doi:10.1016/j.iswcr.2015.11.003

Zahow, M. F., and C. Amrhein. 1992. "Reclamation of a saline sodic soil using synthetic polymers and gypsum." *Soil Science Society of America Journal* **56**:1257–1260.

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11 Organisms and Ecology of the Soil[1]

Under the silent, relentless chemical jaws of the fungi, the debris of the forest floor quickly disappears…
—A. Forsyth and K. Miyata, Tropical Nature

Soil mite Ametroproctus oresbios, center, lends physical jaw-power to the litter decomposition efforts of the other invertebrates and fungi. (Scan Electron Micrograph by Byron Lee, AAFC Lethbridge Research Centre, Lethbridge, AB, Canada, other images courtesy of Ray R. Weil)

The terms *ecosystem* and *ecology* usually call to mind scenes of lions stalking vast herds of wildebeest on the grassy savannas of East Africa or the interplay of phytoplankton, fish, and fishermen in some great estuary. Like a savanna or an estuary, a soil is an ecosystem in which thousands of different kinds of creatures interact and contribute to the global cycles that make all life possible. This chapter will introduce some of the actors in the living drama staged largely unseen in the soil beneath our feet.

If our bodies were small enough to enter the tiny passages in the soil, we would discover a world populated by a wild array of creatures all fiercely competing for every leaf, root, fecal pellet, and dead body that reaches the soil. We would also find predators of all kinds lurking in dark passages, some with fearsome jaws to snatch unwary victims, others whose jellylike bodies simply engulf and digest their hapless prey. But in that world without light, our main sensory apparatus—eyesight—would be useless; we would have to feel our way along the sometimes rough, sometimes slimy surfaces, listen for vibrations, sniff the humid air, and taste the water for chemical signs that might mean food—or danger ahead. Soil organisms find their food and communicate with one another by sensing vibrations, surfaces, chemical gradients, and even electrical fields.

The vast majority of belowground individuals are single microscopic cells whose "jaws" are chemical enzymes that eat away at organic substances left in the soil by their coinhabitants. Some of these enzymes are located inside microbial cells, others may be found in the guts of tiny animals, but many—perhaps most—are found adsorbed to soil particles and in the solution surrounding them, having been excreted by microorganisms into their immediate environment.

The diversity of substrates and environmental conditions found in every handful of soil spawns a diversity of adapted organisms that staggers the imagination. The collective vitality, diversity, and balance among these organisms make possible the functions of a healthy soil. We will learn how these organisms interact with one another, what they eat, how they affect the soil, and how soil conditions affect them. We will come to appreciate how vascular plants live with "one foot in each world"—connecting the above and belowground realms, and how plant roots are soil organisms that play many critical roles in the

[1]For stories about how life underground affects everything on Earth, see Baskin (2005); for soil ecology with emphasis on the meso- and microfauna, see Coleman et al. (2004); for reviews of soil microbiology, see Sylvia et al. (2005), Tate (2015), or Paul (2014).

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life of the soil community. The central theme will be how this community of organisms assimilates plant and animal materials, creating soil organic matter, recycling carbon and mineral nutrients, and supporting plant growth. A subtheme will be how people can manage soils to encourage a healthy, diverse soil community that efficiently makes nutrients available to plants, protects plant roots from pests and disease, and helps protect the global environment from some of the excesses of the human species.

11.1 THE DIVERSITY OF ORGANISMS IN THE SOIL[2]

Soil organisms are creatures that spend all or part of their lives in the soil environment. Every handful of soil is likely to contain billions of organisms, with representatives of nearly every phylum of living things. In this book we will emphasize organisms' activities rather than the scientific classification; consequently, we will consider only very broad, simple taxonomic categories (Table 11.1).

Table 11.1
Some Important Soil Organisms Grouped by Size

Generalized grouping by body width and food source	Major taxonomic groups	Examples
Macro-organisms (>2 mm)		
All heterotrophs: herbivores, detritivores, fungivores, bacterivores, and predators	Vertebrates	Gophers, moles, snakes, salamanders
	Arthropods	Ants, beetles and their larvae, centipedes, grubs, maggots, millipedes, spiders, termites, large collembola
All heterotrophs: herbivores, detritivores, fungivores, bacterivores	Annelids	Earthworms
	Mollusks	Snails, slugs
Largely autotrophs	Vascular plants	Feeder roots
	Bryophytes	Mosses
Meso-organisms (0.1–2 mm)		
All heterotrophs: detritivores, fungivores, bacterivores, and predators	Arthropods	Mites, collembola (springtails), pseudoscorpions
All heterotrophs: detritivores, fungivores, bacterivores	Annelids	Enchytraeid (pot) worms
Microorganisms (<0.1 mm)		
All heterotrophs: detritivores, predators, fungivores, bacterivores	Nematoda	Nematodes
	Rotifera	Rotifers
	Tardigrades	Water bears, *Macrobiotus sp.*
	Protozoa	Amoebae, ciliates, flagellates
Largely autotrophs	Vascular plants	Root hairs
	Algae	Greens, yellow-greens, diatoms
Largely heterotrophs	Fungi	Yeasts, mildews, molds, rusts, mushrooms
Heterotrophs and autotrophs	Bacteria	Acidobacteria, proteobacteria
	Cyanobacteria	Blue-green algae
	Actinobacteria	Streptomyces
	Archaea	Methanotrophs, *Thermoplasma sp.*, halophiles

[2]For beautifully illustrated, up-close and personal introduction to the actors in the soil drama, see Nardi (2007).

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Based on similarities in genetic material, biologists classify all living organisms into three primary domains: ***Eukarya*** (which includes all plants, animals, and fungi), ***Bacteria***, and ***Archaea***. Organisms can also be grouped by what they "eat." Some organisms subsist on living plants (**herbivores**), others on dead plant debris (**detritivores**). Some consume animals (**predators**), some devour fungi (**fungivores**) or bacteria (**bacterivores**), and some live off of, but do not consume, other organisms (**parasites**). **Heterotrophs** rely on organic compounds for their carbon and energy needs while **autotrophs** obtain their carbon mainly from carbon dioxide and their energy from photosynthesis or oxidation of various elements.

Sizes of Organisms. Soil organisms range in size from the tiniest virus to vertebrates some 10,000,000 times larger (Figure 11.1). The animals (*fauna*) of the soil range from **macrofauna** (>2 mm, moles, gophers, earthworms, and millipedes) through **mesofauna** (0.1–2 mm, springtails mites and other arthropods) to **microfauna** (<0.1 mm, nematodes and single-celled protozoans). Plants (*flora*) include the roots of higher plants, as well as single-cell algae and diatoms. **Microorganisms** (too small to be seen without the aid of a microscope) belonging to the fungi, bacteria, and archaea tend to predominate in terms of numbers, mass, and metabolic capacity.

As in any ecosystem, organism abundance is generally inversely related to size. A typical, healthy soil might contain several species of vertebrate animals (mice, gophers, snakes, etc.), a half dozen species of earthworms, 50 species of arthropods (mites, collembola, beetles, ants, etc.), 100 species of nematodes, hundreds of species of fungi, and perhaps thousands of species of bacteria and archaea.

Geographic Diversity. The species that inhabit the soil in a desert will certainly be different from those in a humid forest, which, in turn, will be quite different from those in a cultivated field. Acid soils are populated by species different from those in alkaline soils. Likewise, species presence, diversification, and abundance in a tropical rain forest are different from those in a cool temperate area. Recent studies of sites from around the world using molecular techniques to identify species (or genetically distinct organisms) present and have found that these geographic and soil-related variations in organism diversity are more apparent for soil animals than for microorganisms. While microbial communities almost everywhere contain many of

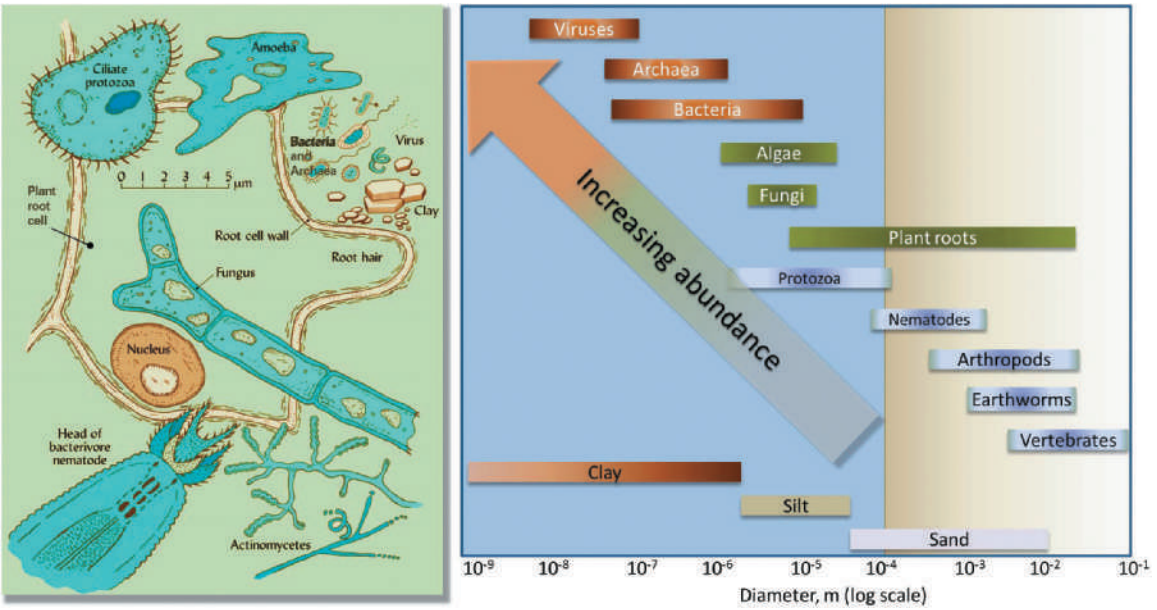

Figure 11.1 *(Left) Representative groups of soil microorganisms, showing their approximate relative sizes. The large white-outlined structure in the center background is a plant root cell. (Right) The size ranges represented by various groups of soil organisms on a logarithmic scale, with size ranges for sand, silt, and clay included for reference. The large arrow indicates that smaller organisms are more numerous.* (Diagrams courtesy of Ray R. Weil)

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the same species and certain common microbial species can be found in almost any soil sample (see Section 11.10), the same is not true for soil animals (Figure 11.2).

Diversity and Isolation. Tremendous diversity is possible because of the nearly limitless variety of foods and the wide range of habitat conditions found in soils. Within a handful of soil there may be areas of good and poor aeration, high and low acidity, cool and warm temperatures, moist and dry conditions, large and small hiding places, and localized concentrations of dissolved nutrients, organic substrates, and competing organisms. The populations of soil organisms tend to be concentrated in zones of favorable conditions, rather than evenly distributed throughout the soil. The soil aggregate (Section 4.5) can be considered a fundamental unit of habitat for meso- and microorganisms, providing a complex range of hiding places, food sources, environmental gradients, and genetic isolation on a microscale. We know that on islands in the middle of the ocean or in valleys surrounded by tall mountains, local populations of birds or insects are genetically isolated and tend to evolve over time into separate species. In the same way, microorganisms living in different aggregates may go down their separate evolutionary paths. The soil provides both spatial diversity and a high degree of genetic isolation, helping to explain why soils contain so many more species of organisms than do aquatic environments (in which the moving fluid media is far more homogenous and provides few physical barriers to genetic commingling).

Types of Diversity. Aquatic ecologists have long considered that a highly diverse community of organisms indicates good water quality in a lake or stream. In the same way, soil scientists are now using the concept of biological diversity as an indicator of soil quality. A high **species diversity** indicates that the organisms present are fairly evenly distributed among a large number of species. Most ecologists believe that such complexity and species diversity are usually paralleled by a high degree of **functional diversity**—the capacity to utilize a wide variety of substrates and carry out a wide array of processes. Ecologists often turn to the soil as a model ecosystem with which to test such fundamental tenets of ecology. Table 11.2 provides an example in which researchers manipulated the level of biodiversity and measured the effects on ecological functions.

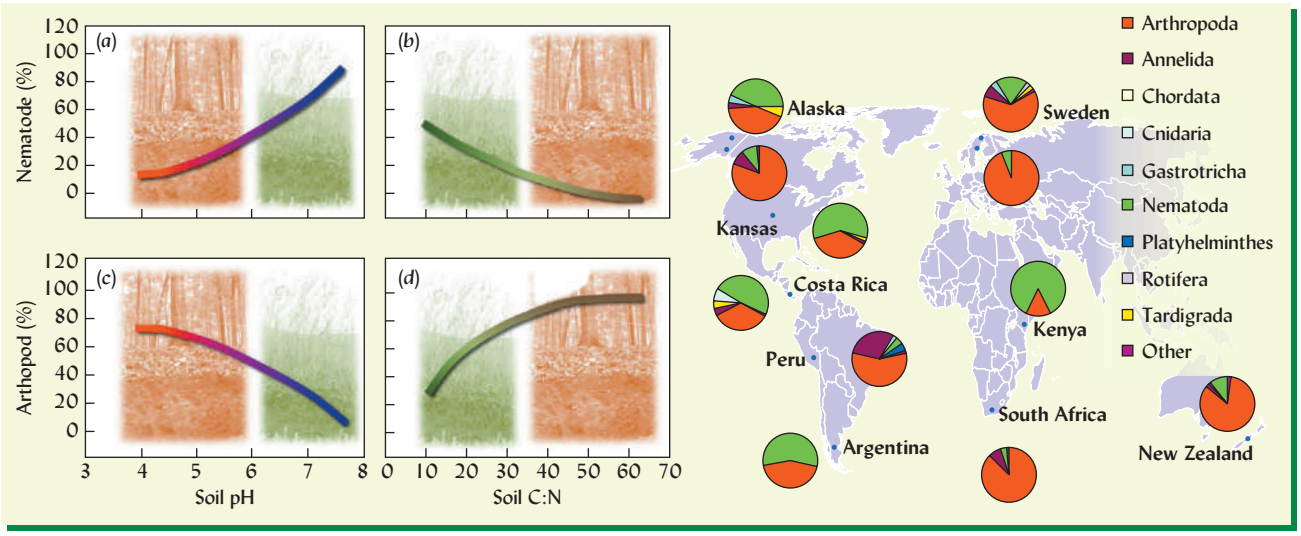

Figure 11.2 *Global distribution of soil animal species is influenced by soil pH and the ratio of C to N in the soil organic matter. In a study of 42 plots at 11 locations around the world (map) some 2259 species of soil animals from ten different major groups (phyla) were identified by molecular techniques. At all the locations, the great majority of species belonged to just two phyla, arthropods (mites and collembola) and/or nematodes (red and green in the small pie charts). In forested soils with low pH levels and high C/N ratios a high percentage of the species present were arthropods, while in grassland soils with higher pH and low C/N ratios more of the species were nematodes.* [Modified from Wu et al. (2011)]

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Table 11.2
THE RELATIONSHIP BETWEEN BIODIVERSITY AND ECOSYSTEM FUNCTION IN A SOIL UNDER GRAZED GRASSLAND VEGETATION

Species diversity was adjusted by fumigating soil samples with chloroform for 0, 0.5, 2, or 24 hours. The longer the fumigation time, the fewer the number of species and individuals that survived. The soils were then incubated for five months. The total abundance and biomass of organisms rebounded to pre-fumigation levels, but consisted only of those species that had survived the fumigation treatments. Soil functions were then measured. Specialized ecological functions (that only a few species can perform) declined consistently with the decrease in biodiversity. In contrast, the more general types of functions (that most species can perform) fluctuated somewhat, but were not significantly affected by the differences in species diversity.

	Hours of initial fumigation			
	0	0.5	2	24
Examples of biodiversity measures				
Bacterial-feeding nematode groups present	8	7	1	0
Flagellate protozoa groups present	23	18	10	5
Examples of general decomposition functions				
Microbial respiration rate, μg CO_2/g per h	0.87	0.37	0.29	0.83
Assimilation of added amino acid, pmol/g per h	90	114	113	159
Examples of specialized ecosystem functions				
Methane oxidation, pg/g per h	77	16	4	−14[a]
Nitrate formation, μg N/g	45	42	24	6

[a]Negative value indicates net methane production rather than oxidation (see Section 12.9).
Data compiled from Griffiths et al. (2000).

Ecosystem Dynamics. In most healthy soil ecosystems there are several—and in some cases many—different species capable of carrying out each of the thousands of different enzymatic or physical processes that proceed every day. This **functional redundancy**—the presence of several organisms to carry out each task—leads both to ecosystem **stability** and **resilience**. *Stability* describes the ability of soils, even in the face of wide variations in environmental conditions and inputs, to continue to perform such functions as the cycling of nutrients, assimilation of organic wastes, and maintenance of soil structure. *Resilience* describes the ability of the soil to "bounce back" to functional health after a severe disturbance has disrupted normal processes (more on this in Section 20.2).

Given a high degree of diversity, no single organism is likely to become completely dominant. By the same token, the loss of any one species is unlikely to cripple the entire system. Nonetheless, for certain soil processes, such as ammonium oxidation (see Section 13.7), methane oxidation (see Section 12.9), or the creation of aeration macropores (see Section 4.8), primary responsibility may fall to only one or a few species. The activity and abundance of a few **keystone species** (e.g., certain nitrifying bacteria or burrowing earthworms) may indicate the health of the entire soil ecosystem.

Genetic Resources. The diversity of organisms in a soil is important for reasons in addition to the safeguarding of ecological functions—soils also make an enormous contribution to **global biodiversity**. Many scientists believe that Earth's land areas host more species belowground than aboveground and that most of those species have yet to be discovered and described. The soil is therefore a major storehouse of the genetic innovations that nature has written into the DNA code over hundreds of millions of years. Humans have always found ways to make use of some of the genetic material in soil organisms (making yogurt

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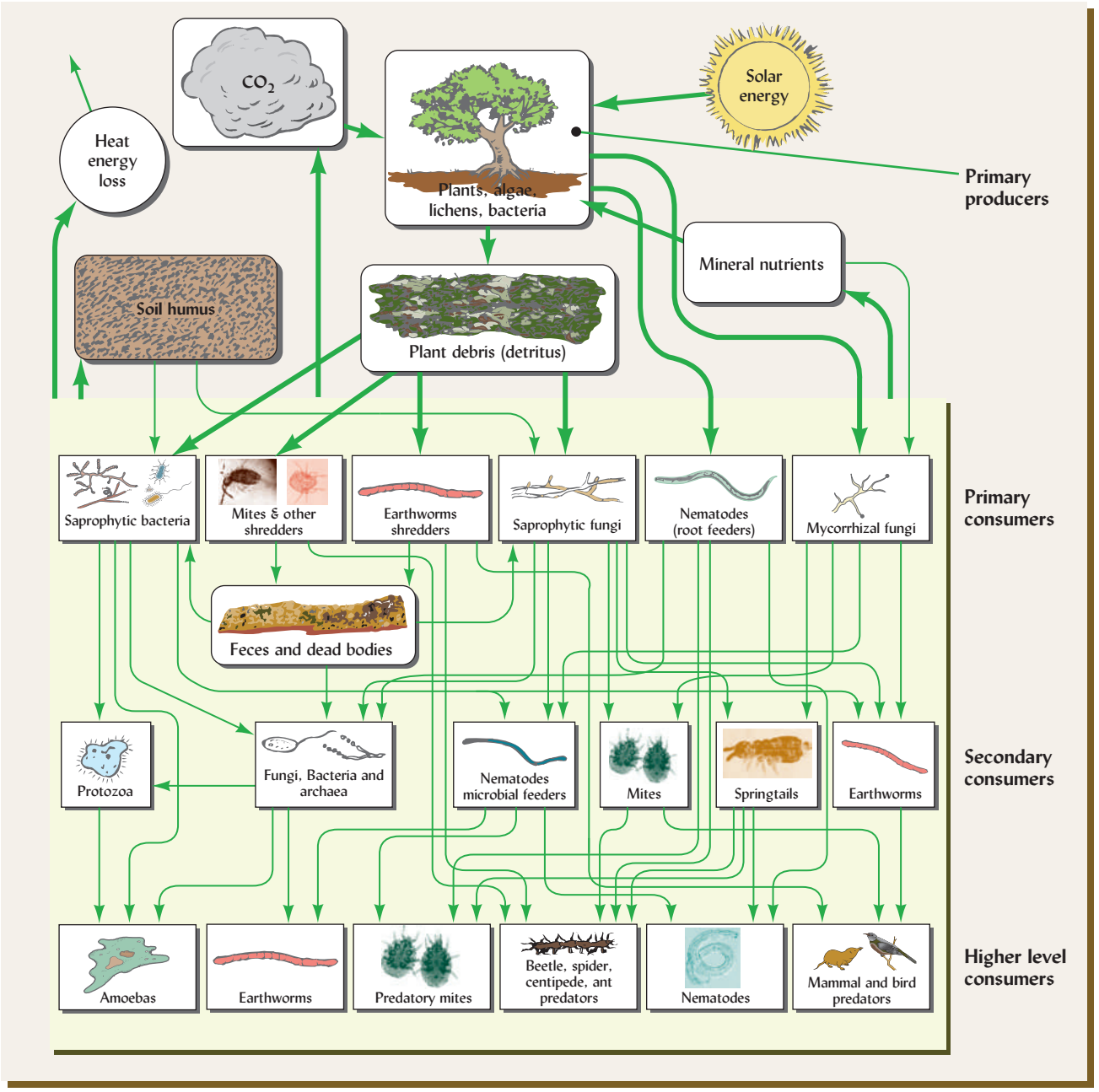

Figure 11.3 *Generalized diagram of the soil food web involved in the breakdown of plant tissue, the formation of humus, and the cycling of carbon and nutrients. The large shaded compartment represents the community of soil organisms. The rectangular boxes represent various groups of organisms; the arrows represent the transfer of carbon from one group to the next as predator eats prey. The thick arrows entering the top of the shaded compartment represent primary consumption of carbon originating from the tissue of the producers—green plants, algae, and cyanobacteria. The rounded boxes represent other inputs that support, and outputs that result from, the soil food web. Although all groups shown play important roles in the process, some 80–90% of the total metabolic activity in the food web can be ascribed to the microbes: fungi, bacteria, and archaea. As a result of this metabolism, soil is created and stabilized, and carbon dioxide, heat energy, and mineral nutrients are released into the soil environment.* (Diagram courtesy of Ray R. Weil)

is an example). In modern times antibiotic medicines derived from soil microbes have played a major role in saving human lives.

Molecular biology now enables scientists to identify microbial genes that code for the production of countless enzymes and secondary metabolites, many of which may prove to be compounds useful to humans. Meanwhile, advances in bioengineering allow the transfer of

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such genetic material from one type of organism to another, opening up the possibility that genes from soil organisms may be used to produce useful compounds at industrial scale and create plants and animals of superior utility to the human community. Thus soil biodiversity—and the protection of this incredible DNA bank—has now taken on a new and much greater practical significance for human welfare. Examples are as diverse as soil microbial enzymes that efficiently catalyze the reduction of CO_2 to store H_2 for fuel cells to soil microbial biomolecules that have potential as cancer-fighting drugs.

11.2 ORGANISMS IN ACTION[3]

Trophic Levels and the Soil Food Web

As one organism "eats" or metabolizes its food, the nutrients and carbon contained therein are said to be passed from one **trophic level** to a higher one. The first trophic level is that of the **primary producers** such as green plants that *produce* energy-rich organic substances from abiotic components of the environment (sunlight, CO_2, etc.). The second trophic level consists of the **primary consumers** that eat those producers or their dead products. The third trophic level would be those **predators** and **microbial feeders** that eat the primary consumers; the fourth level would be predators that eat predators, and so on. The complex web of arrows in Figure 11.3 illustrate why ecologists describe these relationships with the term **food *web*** rather than the commonly used term food *chain*.

Sources of Energy and Carbon

Soil organisms may be classified as either **autotrophic** or **heterotrophic** based on where they obtain the *carbon* needed to build their cell constituents (Table 11.3). Heterotrophic soil organisms obtain their carbon from the breakdown of organic materials previously produced by other organisms. Nearly all heterotrophs also obtain their *energy* from the oxidation of the carbon in organic compounds. They are responsible for organic decay and most soil food web

Table 11.3
METABOLIC GROUPING OF SOIL ORGANISMS ACCORDING TO THEIR SOURCE OF METABOLIC ENERGY AND THEIR SOURCE OF CARBON FOR BIOCHEMICAL SYNTHESIS

	Source of energy	
Source of carbon	**Biochemical oxidation**	**Solar radiation**
Combined organic carbon	**Chemoheterotrophs:** All animals, plant roots, fungi, actinomycetes, and most bacteria Examples: Earthworms *Aspergillus sp.* *Azotobacter sp.* *Pseudomonas sp.*	**Photoheterotrophs:** A few algae
Carbon dioxide or carbonate	**Chemoautotrophs:** Some bacteria, many archaea Examples: Ammonia oxidizers—*Nitrosomonas sp.* Sulfur oxidizers—*Thiobacillus denitrificans*	**Photoautotrophs:** Plant shoots, algae, and cyanobacteria Examples: *Chorella sp.* *Nostoc sp.*

[3]For a succinct and well-illustrated summary of soil communities and ecological dynamics, see USDA/NRCS (2000). For a discussion of some basic principles of soil ecology and function see Fierer et al. (2009). For a fascinating video of micro and meso fauna in action, see https://www.youtube.com/watch?v=VuHznslr8aI.

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processes. These organisms, which include all soil animals, the fungi, actinomycetes, and most other bacteria, are far more numerous than the autotrophs.

The autotrophs obtain their carbon from simple carbon dioxide gas (CO_2) or carbonate minerals, rather than from carbon already fixed in organic materials. Autotrophs can be further classified based on how they obtain energy. Some use solar energy (photoautotrophs), while others use energy released by the oxidation of inorganic elements such as nitrogen, sulfur, and iron (chemoautotrophs). While the autotrophs are in the distinct minority, their carbon fixation and inorganic oxidation reactions allow them to play crucial roles in the soil system. The autotrophs are mainly algae, cyanobacteria, and certain other bacteria and archaea. The aboveground shoots of plants are autotrophic, while the belowground roots behave somewhat as heterotrophs, metabolizing organic compounds synthesized by the shoot and transported to the root.

Primary Producers

As in most aboveground ecosystems, vascular plants play the principal role as primary producers. By combining carbon from atmospheric carbon dioxide with water, using energy from the sun, the producer organisms make organic molecules and living tissues. In this, they are commonly joined by mosses, algae, lichens, and photosynthesizing bacteria. In certain environments, other primary producers are found that use inorganic chemical reactions to obtain energy to make living cells. In any case, the organic materials created by the primary producers contain both carbon and chemical energy that other organisms can utilize, either directly or indirectly, after having been passed on through intermediaries. The producers therefore form the food base for the entire soil food web.

Primary Consumers

As soon as a leaf, a stalk, or a piece of bark drops to the ground, it is subject to coordinated attack by microbes and by macro- and mesofauna (see Figure 11.3). Animals, including mites (see chapter opener image), collembola, woodlice, and earthworms, chew or tear holes in the tissue, opening it up to more rapid attack by the microbes. The animals and microbes that use the energy stored in the plant residues are termed *primary consumers*.

Herbivores. Soil organisms that eat live plants are called **herbivores**. Examples are parasitic nematodes and insect larvae that attack plant roots, as well as termites, ants, beetle larvae, woodchucks, and mice that devour above- or belowground plant parts. Because they attack living plants that may be of value to humans, many of these soil herbivores are considered pests. On the other hand, certain herbivores, such as soil-dwelling immature cicadas, commonly do more good than harm for higher plants (Figure 11.4).

Detritivores. For the vast majority of soil organisms, however, the principal source of food is the debris of dead tissues left by plants on the soil surface and within the soil pores. This debris is called **detritus**, and the animals that directly feed on it are called **detritivores**. Both herbivores and detritivores that eat the tissues of primary producers are considered primary consumers. However, many of the animals that chew up plant detritus actually get most of their nutrition from the microorganisms that live in the detritus, not from the dead plant tissues themselves. Such animals are not really primary consumers (second trophic level), but belong to higher trophic levels as they metabolize either primary consumers microbes or the detritus from other animals (fecal pellets, dead bodies) (see "Secondary Consumers," following).

Saprophytic Microorganisms. On balance, most actual decomposition of dead plant and animal debris is carried out by **saprophytic** (feeding on dead tissues) microorganisms: fungi, bacteria, and archaea. With the assistance of the animals that physically shred and chew the plant debris (see following), the saprophytes break down all kinds of plant and animal compounds, from simple sugars to woody materials (Figure 11.3). Saprophytes feed on detritus, dead animals (corpses), and animal feces. These microorganisms commonly grow to form large colonies of microbial cells on the decaying material. These microbial colonies, in turn, soon provide nutrition to a myriad of other soil organisms—the secondary consumers.

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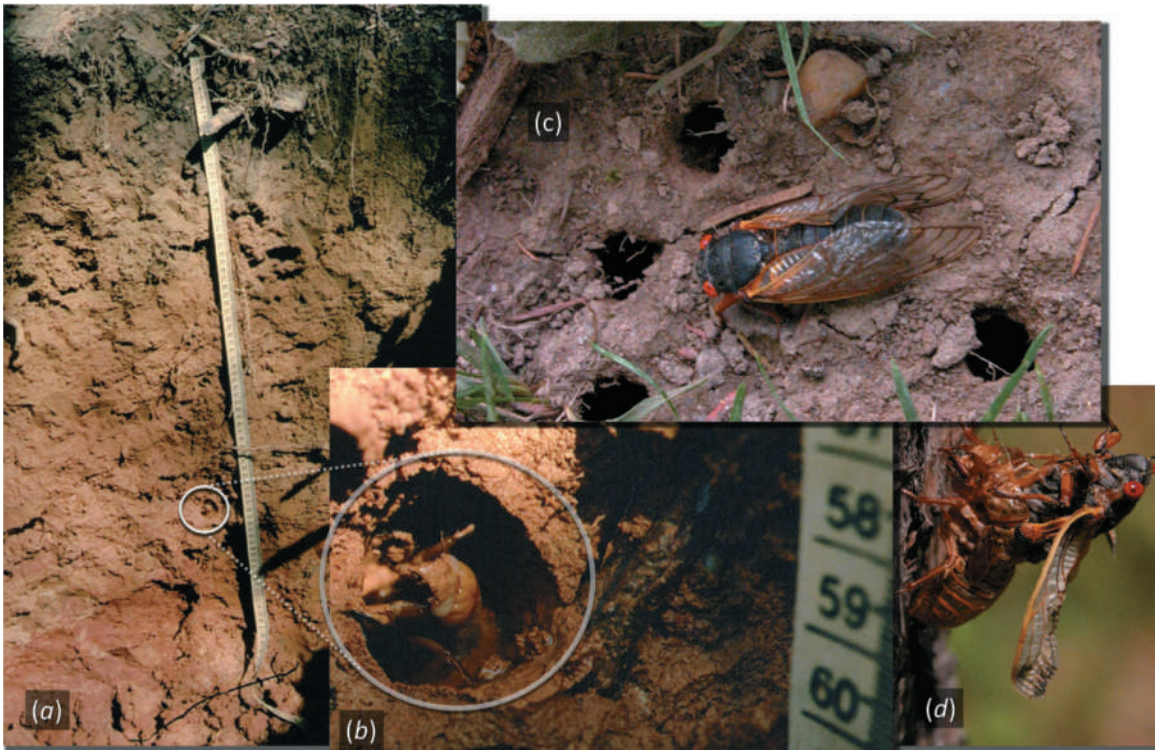

Figure 11.4 *The North American 17-year cicada lives in the soil 99% of the time. (a) A cicada nymph (Magicicada spp.) nestled 60 cm deep in the B horizon of a forested Ultisol feeds by sucking sap from oak tree roots, making it both a primary consumer and a herbivore. This feeding is not thought to cause significant damage to the trees. In fact, the burrowing activity of this below ground insect aids soil drainage and may enhance the trees' root growth. (b) A closer view reveals the nymph sucking on a root while bathed in drainage water in a soil macropore of its own creation. (c) After 17 years of living belowground, the biological clock in this cicada—in synch with millions of its broodmates—will let it know it's time to burrow its way to the surface, crawl out of an emergence hole (four such holes and an adult cicada are shown), molt one last time (d) and as an adult, spend a week or two aboveground mating, laying eggs in tree branches, and then dying. Even in death these creatures impact the ecosystem as millions per ha decay, providing a major pulse of nutrients that results in a spurt of tree growth and subsequent spikes in deer and squirrel populations. It is no wonder that this unique creature is the subject of continuing ecological research (Sota et al., 2013; Yang, 2004).* (Photos courtesy of Ray R. Weil)

Secondary Consumers

Predators and Microbial Feeders. The bodies (cells) of primary consumers become food sources for an array of predators and parasites in the soil. These *secondary consumers* include microbes, such as bacteria and fungi, as well as **carnivores**, animals which consume other animals. Examples of carnivores include centipedes (Figure 1.8) and mites that attack small insects or nematodes (see Figure 11.5), spiders, predatory nematodes, and snails.

Microbivorous feeders, organisms that use microbes as their source of food, include certain collembola (springtails), mites (Figure 11.6), termites, certain nematodes (see chapter opening photo), and protozoa. These microphytic feeders exert considerable influence over the activity and growth of fungal and bacterial populations. The grazing by these meso- and microfauna on microbial colonies may stimulate faster growth and activity among the microbes, in much the same way that grazing animals can stimulate the growth of pasture grasses. In other cases, the attack of the microphytic feeders may kill off so much of a microbial colony as to inhibit the work of the microorganisms.

Stimulation of Decomposition. While the actions of the microbes are mostly biochemical, those of the fauna are both physical and chemical. The mesofauna and macrofauna chew the plant residues into small pieces and move them from one place to another in or on the soil.

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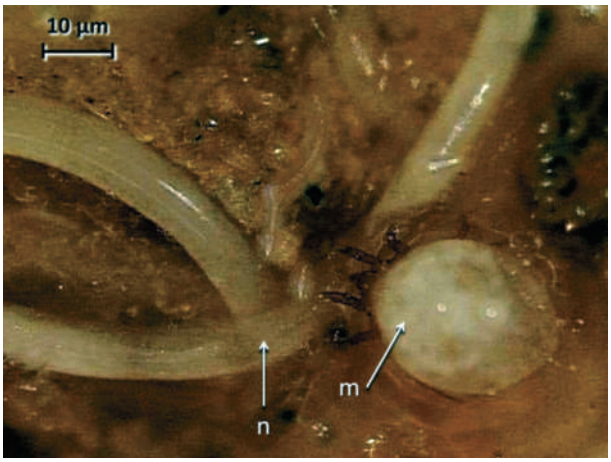

Figure 11.5 *A predatory mite (an Astigmatid, m) dining on its prey, a microscopic roundworm (a nematode, n). Predation of this type keeps the populations of various groups of organisms in balance and releases nutrients previously tied up in the bodies of the prey.* (Carmen Marie Greenwood)

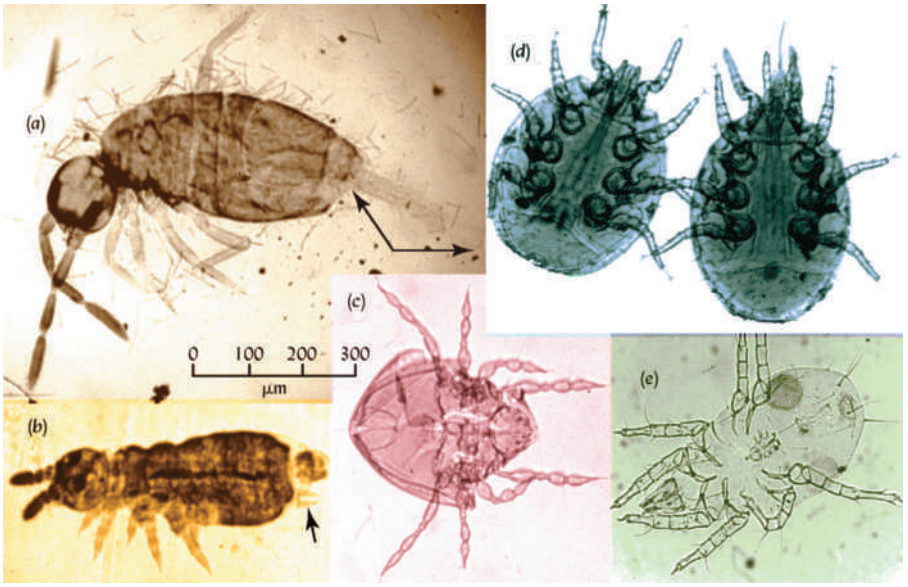

Figure 11.6 *Collembola (a,b) and mites (c,d,e) are prominent among the mesofauna that play important roles in soil food webs. Collembola are also called springtails because of their springlike furcula or "tail" (arrows). The larger springtail (a) lives in and on the O horizons where there is light to see (hence the operational eyes) and room to hop (hence the well-developed furcula). The smaller springtail (b) lives in the mineral soil horizons where there is no light and no room to hop (hence it has only tiny vestigial "eyes" and furcula). Both springtails shown probably eat detritus and the fungi growing in it. The Orabatid mite (c) also feeds on detritus. The Mesostigmatic mites (d,e) are predators of smaller arthropods, nematodes, and other denizens of the soil. Note that mites (arachnids) have eight legs, while springtails (insects) have six.* (Photos courtesy of Ray R. Weil)

The actions of these animals enhance the activity of the microbes in several ways. First, the chewing action fragments the litter, cutting through the resistant waxy coatings on many leaves to expose the more easily decomposed cell contents for microbial digestion. Second, the chewed plant tissues are thoroughly mixed with microorganisms in the animal gut, where conditions are ideal for microbial activity. Third, the mobile animals carry microorganisms with them and help the latter to disperse and find new food sources to decompose. The effect of excluding different sizes of soil fauna on the rate plant residue decomposition is illustrated in Figure 11.7.

Tertiary Consumers

Predators. In the next level of the food web, the secondary consumers are prey for *tertiary consumers*. For example, ants consume centipedes, spiders, mites, and scorpions—all of which can themselves prey on primary or secondary consumers. Many species of birds specialize in eating soil animals such as beetles and earthworms. Robins are widely known to pull earthworms from their burrows, while other birds such as gulls and blackbirds commonly follow behind a farmer's plow to feed on the exposed earthworms and other soil macrofauna. Such mammals as moles can be effective predators of macrofauna. Whether the prey is a nematode or an earthworm, predation serves important ecological functions, including the release of nutrients tied up in the living cells.

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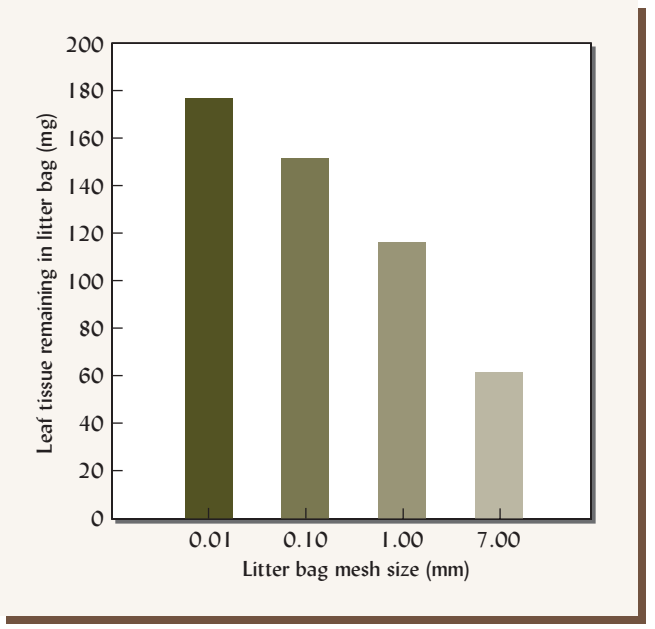

Figure 11.7 *Influence of various sizes of soil organisms on the decomposition of corn leaf tissue buried in soil. Small bags made of nylon mesh material with four different-size openings (mesh size) were filled with 558 mg (dry weight) of corn leaf tissue and buried in the soil for ten weeks. The amount of corn leaf tissue remaining in the bags was considerably greater (less decomposition had taken place) when the meso- and macrofauna were excluded by the smaller mesh sizes.* [Data from Weil and Kroontje (1979)]

Microbial Decomposers. Microorganisms are intimately involved in every level of decomposition. Some live feely on soil particle and plant root surfaces; others exist within larger organisms in the soil. Thus, some microbes directly attack plant tissues (as primary consumers), while other microorganisms active within the digestive tracts of soil animals help these animals digest more resistant organic materials. Microbes also attack the finely shredded organic material in animal feces, as well as decompose the bodies of dead animals. For these reasons, while soil animals may chew on organic materials, the microbes are referred to as the ultimate decomposers.

Diversification Within Broad Groups. As indicated in Figure 11.3, broad groups of organisms, such as fungi or mites, include some species that are primary consumers, some that are secondary consumers, and others that are tertiary consumers. For example, some mites attack detritus directly, while others eat mainly fungi or bacteria that grow on the detritus. Still others attack and devour the mites that eat fungi. Two-way interactions exist between many groups of organisms. For example, some nematodes eat fungi, and some fungi attack nematodes.

Ecosystem Engineers[4]

Certain organisms make major alterations to their physical environment that influence the habitats of many other organisms in the ecosystem. These organisms are sometimes referred to as *ecosystem engineers*. For example, some of these "engineer" species are microorganisms that create an impermeable surface crust that spatially concentrates scarce water supplies in certain desert soils.

Burrowing Animals. Others ecological engineers are burrowing animals that create opportunities and challenges for other organisms by digging channels that greatly alter air and water movement in soils. Termites (see Section 11.5) and ants, for example, may literally invert the soil profile in local areas (bringing subsoil material to the surface) and denude the soil surface in wide areas. Earthworms create extensive channels through the soil

[4]For a discussion of the ecosystem engineer concept in soils, see Jouquet et al. (2006) and Lavelle et al. (1997). For applications of the concept to coral reef and desert soils, see Alper (1998).

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Figure 11.8 *A dung beetle (Scarabaeidae) rolls a ball that it has fashioned out of cow dung on a pasture soil in Tanzania. The female will lay her eggs in the ball of dung and bury it in the soil. Burying the dung is very important for making the nutrients therein available to the soil food web. Dung burial also prevents the reproduction of carnivorous flies and other pests of dung-producing mammals. Different dung beetles have evolved to specialize in the burial of dung from particular species of animals.* (Photo courtesy of Ray R. Weil)

and incorporate plant residues into the mineral soil by passing them through their bodies along with mineral soil particles (see Section 11.4). Larger animals, such as gophers (see Figure 2.30), moles, prairie dogs, and rats, also burrow into the soil and bring about considerable soil mixing and granulation. Not only do such burrows encourage more water and air to enter the soil, they also provide passages that plant roots can easily follow to penetrate dense subsurface soil layers. Furthermore, the underground chambers and burrows made by the engineers provide new kinds of habitat in which other organisms (from frogs to fungi) soon take up residence.

Dung Beetles. Certain beetles of the *Scarabaeidae* family greatly enhance nutrient cycling by burying animal dung in the upper soil horizons. Many of these **dung beetles** cut round balls from large mammal feces, enabling them to roll the dung balls to a new location (Figure 11.8). The female dung beetle then lays her eggs in the ball of dung and buries it in the soil. Dispersal and burial of the dung not only provides a food source for the beetle larvae, but also protects the nutrients in the manure from easy loss by runoff or volatilization—fates to which the nutrients would most likely succumb if left on the soil surface. Dung beetles therefore play important roles in nutrient cycling and conservation in many grazed ecosystems.

Several thousand different dung beetle species are known worldwide, many having evolved to specialize in the burial of dung from particular mammal species (elephant, cattle, buffalo, etc.). Rapid burial of dung by beetles also prevents the reproduction of carnivorous flies and other pests of large dung-producing mammals. Where native dung-burying "engineer" species are lacking in a grazed ecosystem (such as a savanna, a prairie, or a pasture), scientists have found that the introduction of appropriate species of dung beetles or earthworms can greatly increase the amount of vegetation produced and the number of grazing animals supported.

11.3 ABUNDANCE, BIOMASS, AND METABOLIC ACTIVITY

Soil organism numbers are influenced primarily by the amount and quality (especially the carbon and nitrogen content) of food available. Other factors affecting their numbers include physical factors (e.g., moisture and temperature), biotic factors (e.g., predation and competition), and chemical characteristics of the soil (e.g., pH, dissolved nutrients, and salinity). Cultivated fields are generally lower than undisturbed native lands in numbers

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and biomass of soil organisms, especially the fauna, partly because tillage destroys much of their soil habitat.

Total **soil biomass**, the living fraction of the soil, is generally related to the amount of organic matter present. On a dry-weight basis, the living portion is usually between 1 and 5% of the total soil organic matter (see Section 12.6). To put this amount of biomass in perspective, one hectare of surface soil containing 3% soil organic matter might contain 600–3000 kg (1–5 pickup truck loads) of living creatures—not counting the plant roots!

Comparative Organism Activity

The importance of specific groups of soil organisms is commonly identified by: (1) the numbers of individuals in the soil, (2) their weight (biomass) per unit volume or area of soil, and (3) their metabolic activity (often measured as the amount of carbon dioxide given off in respiration). The numbers and biomass of groups of organisms that commonly occur in soils are shown in Table 11.4. Although the relative metabolic activities are not shown, they are generally related to the biomass of the organisms. Representative measurements of soil biological activity are not easily made because the soil is such a heterogeneous medium and the organisms living in it are very unevenly distributed. Concentrations of microbial activity (hotspots) occur in the immediate vicinity of living plant roots and decaying bits of detritus, in the organic material lining earthworm burrows, in fecal pellets of soil fauna, and in other favored soil environments.

As might be expected, the microorganisms are the most numerous and have the highest biomass. Together with earthworms (or termites, in the case of some tropical soils), the microorganisms dominate the biological activity in most soils, although, as previously mentioned, their activity is enhanced by the actions of soil fauna. Despite their relatively small total biomass, such microfauna as nematodes and protozoa play important roles in nutrient cycling by preying on bacteria and fungi.

Table 11.4
NUMBERS AND BIOMASS OF ORGANISMS COMMONLY FOUND IN SURFACE SOIL HORIZONS
Microorganisms and earthworms dominate the biomass of most humid region soils.

	Biodiversity	Number[a]		Biomass[b]	
Organisms	Taxa[c]	Per m^2	Per g	kg/ha	g/m^2
Microorganisms					
Bacteria and Archaea[d]	1–9,000/g	10^{14}–10^{15}	10^{9}–10^{10}	400–5,000	40–500
Actinomycetes		10^{12}–10^{13}	10^{7}–10^{8}	400–5,000	40–500
Fungi	1–300/g	10^{6}–10^{8} m	10–10^{3} m	1,000–15,000	100–1,500
Algae	—	10^{9}–10^{10}	10^{4}–10^{5}	10–500	1–50
Fauna					
Protista (protozoa)	1–5,000/g	10^{7}–10^{11}	10^{2}–10^{6}	20–300	2–30
Nematodes	10–1,000/m^2	10^{5}–10^{7}	1–10^{2}	10–300	1–30
Mites	100–500/m^2	10^{3}–10^{6}	1–10	2–500	0.2–5
Collembola	10–100/m^2	10^{3}–10^{6}	1–10	2–500	0.2–5
Earthworms	2–10/m^2	10–10^{3}		100–4,000	10–400
Other fauna	30–3,000/m^2	10^{2}–10^{4}		10–100	1–10

[a]A fungus individual is hard to define, so abundance is given as meters hyphal length.
[b]Biomass values are on a live weight basis. Dry weights are about 20–25% of these values.
[c]Species or genome equivalents per unit of soil (g or m^2 of A horizon).
[d]Estimated numbers of bacteria and archaea from Torsvik et al. (2002); biodiversity estimates based on Bardgett and van der Putten (2014); other estimates from many sources.

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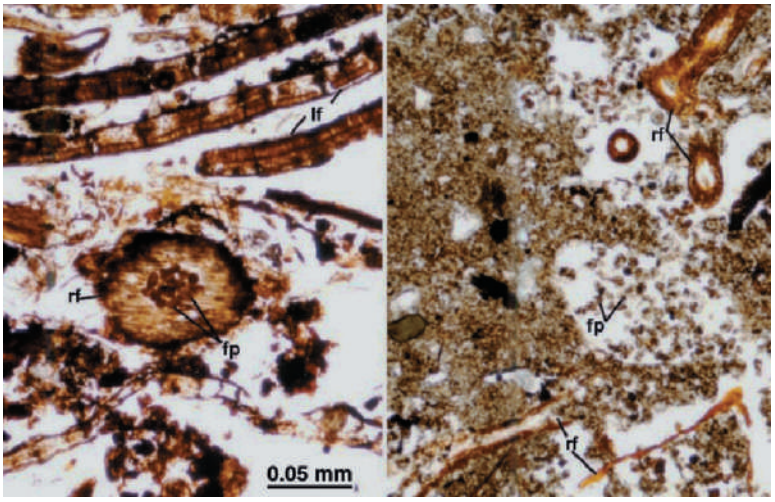

Figure 11.9 *Influence of mesofauna on soil structure in an O horizon (left) and A horizon (right) of a forested Ultisol in Tennessee, USA. The labeled features include leaf fragments (lf), root fragments (rf), and fecal pellets (fp). In the O horizon, the fecal pellets were left by mites that were eating out the inside of a pine tree needle (seen in cross section). In the A horizon, fecal pellets are seen in an oval biopores.* (Debra Phillips/Queen's University Belfast)

Even those animals that account for only very small fractions of the total metabolism in the soil can play important roles in soil formation (see Chapter 2) and function. Rodents pulverize, mix, and granulate soil, as well as incorporate surface organic residues into lower horizons. They provide large channels through which water and air can move freely. Ants are important in localized areas, especially in warm-region grasslands and in boreal forests, for their exceptional ability to break down woody materials and turn over soil materials as they build their nests. Mesofauna detritivores (mostly mites and collembola; see Figure 11.6) translocate and partially digest organic residues and leave their excrement for microbial degradation (see Figure 11.9). By their movements in the soil, many animals rearrange soil particles to form biopores, thus favorably affecting the soil's physical condition (also visible in Figure 11.9). Other animals, especially certain insect larvae, feed directly on plant roots, causing considerable damage (see Sections 11.7 and 11.13).

In this chapter we will focus largely on both microorganisms and certain keystone or ecological engineering macrofauna. We will begin with the earthworms.

11.4 EARTHWORMS[5]

Earthworms (along with their much smaller cousins, the **enchytraeid worms**) are egg-laying *hermaphrodites* (organisms without separate male and female genders) that eat detritus, soil organic matter, and microorganisms found on these materials (Figure 11.10). They do not eat living plants or their roots, and so do not act as pests to crops. Earthworms are often keystone species in soil ecosystems and can have major impacts on soil function.

Epigeic, Endogeic, and Anecic Earthworms. The 7000 or so species of earthworms reported worldwide can be grouped according to their burrowing habits and habitat. The relatively small **epigeic** earthworms live in the litter layer or in the organic-rich soil very near the surface. Epigeic earthworms, which include the common compost worm, *Eisenia foetida*, hasten decomposition of litter but do not mix it into the mineral soil. **Endogeic** earthworms, such as the pale, pink *Allolobophora caliginosa* (known as "red worm"), live mainly in the upper 10–30 cm of mineral soil where they make shallow, largely horizontal burrows. Finally, the large **anecic** earthworms make vertical, relatively permanent burrows as much as several meters deep. They emerge in wet weather or at night to forage on the surface for pieces of litter that they drag back into their burrows, often covering the entrance to their burrow with a **midden** of

[5]For extensive information on earthworm ecology, biology, and distribution, see Edwards (2004). For a review of earthworm impacts on soil ecosystem services, see Blouin et al. (2013). Edwards and Arancon (2004) provide a good discussion of earthworms in relation to agriculture, soil organic matter, and soil microbiology.

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Figure 11.10 *Anecic earthworm species such as these* Lumbricus terrestris *(a) come to the surface to feed on litter (c), excrete soil casts (a, arrows), and reproduce (b). They incorporate large amounts of plant litter into the soil and gather plant debris into piles called middens to cover their burrow entrances (d, 10 cm scale markings). Earthworms are perhaps the most significant macroorganism in soils of humid temperate regions, particularly in relation to their effects on the physical conditions of soils.* (Photos (a) and (d) courtesy of Ray R. Weil; photos (b) and (c) courtesy of Steve Groff)

leaves (Figure 11.10*d*). The well-known "night crawler" (*Lumbricus terrestris*) was accidentally introduced to North America from Europe (perhaps in the root balls of settlers' fruit trees) and is now the most common anecic earthworm on both continents.

Influence on Soil Fertility, Productivity, and Environmental Quality

Burrows. Earthworms burrow through the soil by first elongating and narrowing their flexible bodies, "worming" into an existing cracks or plane of weakness, and then exerting considerable lateral pressure to thicken their bodies and so widen the passage as they move ahead. In so doing, they create extensive systems of channels which may be empty or filled with earthworm casts. These channels offer important pathways by which plant roots can penetrate dense soil layers, especially in compacted soils (Figure 11.11*b*). Their extensive physical activity, which is particularly important in untilled soils (including grasslands and no-till croplands) has earned earthworms the title of "nature's tillers" (see Figure 11.11). The middens of plant litter and the circular burrow entrances (often hidden by middens) are important signs used to assess earthworm activity (Figure 11.10*d*).

Casts. In addition to plant litter, earthworms also ingest a great deal of soil—perhaps to 2–30 times their own weight of soil in a single day. In a single year, the earthworms in grassland and forest ecosystems typically ingest and process between 20 and 1000 Mg of soil, the higher figure occurring on fertile soils in moist, tropical climates. After passing through the earthworm gut, ingested soil is expelled as globules called **casts** (Figure 11.10*a*). During the passage through the earthworm's gut, organic materials are thoroughly shredded and soil microaggregates are broken down, with new aggregates formed from the mineral and organic materials. Probably because of enhanced bacterial activity, earthworm casts are usually high in polysaccharides, which are credited with stabilizing the casts into granular structure (see Section 4.5). The casting behavior of earthworms generally enhances aggregate stability and nutrient availability to plants (Table 11.5). The casts deposited within the soil profile or on

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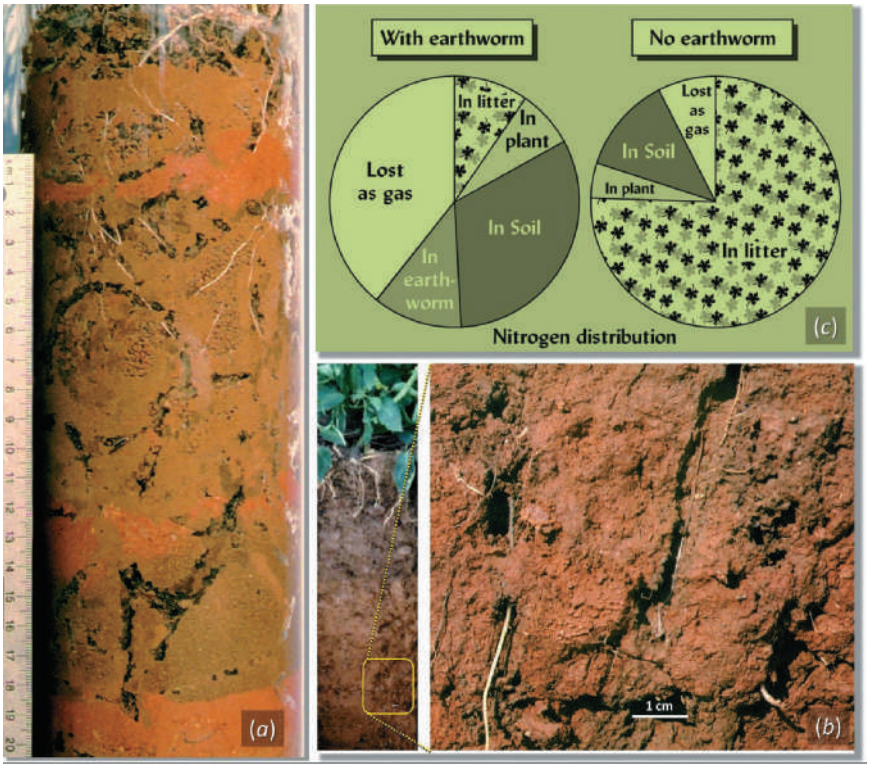

Figure 11.11 *Burrowing activities of earthworms and their effects on plant roots and the distribution of nitrogen from plant litter. (a) A glass cylinder was pack with layers of A and B horizon soil and wrapped to exclude light. The soil was moistened, a few grass seeds planted, a layer of leaves placed on the soil surface, and two anecic earthworms added. The photo, taken one week later, shows the soil riddled with burrows (some occupied by grass roots).(b) The profile of a compacted Inceptisol under tomatoes after15 years of no-till management using cover crops. The close-up shows tomato roots following organic matter lined earthworm channels through the subsoil at about 60–70 cm deep. (c) Data from soil columns (called mesocosms) in which corn litter labeled with* ^{15}N *(isotope of nitrogen) was incubated for 3 weeks with or without an earthworm (Lumbricus terrestris). After the incubation, the earthworms and remaining litter were removed, and corn plants were grown for 30 days. Without earthworms, most of the N remained in the litter. In contrast, the earthworms made nearly all the N available for biological processes, including plant uptake (which nearly doubled) and gaseous losses (which increased fivefold) (see Sections 13.6 and 13.9). Such studies demonstrate that earthworms dramatically hasten the cycling of nutrients in the soil–plant system.*
[Photos courtesy of Ray R. Weil; charts based on data in Amador and Gorres (2005)]

the soil surface, depending on the species of earthworm, are another sign used to assess earthworm activity in soil.

Nutrients. Earthworms hasten the cycling and increase the availability of mineral nutrients to plants in three ways. First, as soil and organic materials pass through an earthworm, they are ground up physically as well as attacked chemically by the digestive enzymes of the earthworm and its gut microorganisms. Compared to the bulk soil, the casts are significantly higher in bacteria, organic matter, and available plant nutrients (see Table 11.5). Roots growing down earthworm burrows also find rich sources of nutrients in the casts and burrow lining material.

Table 11.5
Comparative Characteristics of Earthworm Casts and Soils

Average of six Nigerian soils

Characteristic	Earthworm casts	Soils
Silt and clay, %	38.8	22.2
Bulk density, Mg/m^3	1.11	1.28
Structural stability[a]	849	65
Cation exchange capacity, cmol/kg	13.8	3.5
Exchangeable Ca^{2+}, cmol/kg	8.9	2.0
Exchangeable K^+, cmol/kg	0.6	0.2
Soluble P, ppm	17.8	6.1
Total N, %	0.33	0.12

[a]Number of raindrops required to destroy structural aggregates.
From de Vleeschauwer and Lal (1981).

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Second, although earthworms may feed on detritus and soil organic matter of relatively low nitrogen, phosphorus, and sulfur concentrations, their own body tissues have high concentrations of these nutrients. When the earthworms die and decay, the nutrients in their bodies are readily released into plant-available form. Studies have shown that where earthworm populations are large, a major proportion of the N taken up by plants (50–90 kg N/ha) can be made available by this mechanism.

Third, physical incorporation of animal droppings and plant litter into the soil reduces the loss of nutrients, especially of nitrogen, by erosion and ammonia gas volatilization. However, the same action may increase losses by other pathways (Figure 11.11, *pie charts*).

Beneficial Physical Effects. Earthworms are important in other ways. The holes left in the soil (see, e.g., Figure 6.9) serve to increase aeration and drainage, an important consideration in plant productivity and soil development. In turfgrass, the mixing activity of earthworms can alleviate or reduce compaction problems and nearly eliminate the formation of an undesirable thatch layer. Under conditions of heavy rainfall, earthworm burrows may greatly increase the infiltration of water into the soils and reduce erosion of agricultural soils, but these benefits are dependent on farming practices that return large amounts of crop residues (Figure 11.12).

Deleterious Effects of Earthworms

Exposure of Soil on the Surface. Not all effects of earthworms are beneficial. For example, in the process of building its middens, *Lumbricus terrestris* has been observed to leave some 60% of the soil surface bare of residues (see Figure 11.10*d*). To some extent this action leaves the exposed soil susceptible to the impact of raindrops, crust formation, and increased erosion. In other situations, the middens themselves may be considered a nuisance—for example, on closely cropped golf greens. Even the burrowing and litter incorporation activities may not always be welcome—as in forests ecosystems with thick litter layers (see Box 11.1).

Influence on Chemical Leaching. Another aspect of concern is that water rapidly percolating down vertical earthworm burrows may carry potential pollutants toward the groundwater (see Figure 6.34). In artificially drained fields, earthworm channels may provide direct paths from the soil surface to the drain tiles, leading to increased leaching losses of soluble agri-chemicals and nutrients. However, the organic matter–enriched material lining earthworm burrows has two to five times as great a capacity to adsorb certain herbicides as the bulk soil. Therefore, transport of such pollutants through earthworm burrows may be much less than is suggested by the mass flow of water through these large biopores.

Increased Greenhouse Gas Emissions.[6] Earthworms present something of a soil conundrum because the same activities that promote organic matter incorporation and nutrient

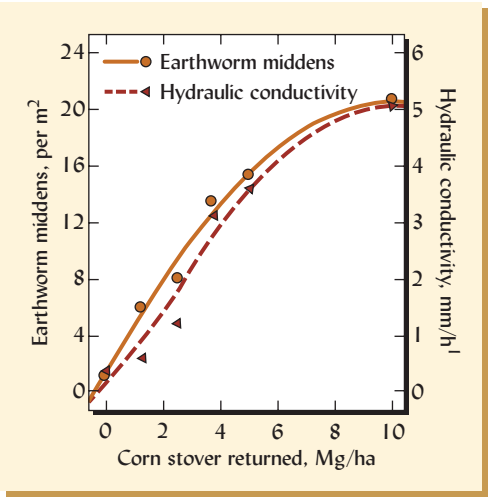

Figure 11.12 *Influence of crop residue on earthworm activity and soil hydraulic conductivity. The lower rates of residue return represent the situations when some or all of the corn stover is collected and removed for the production of ethanol biofuel or corn silage. The graph shows the effect of just one year of differing stover returns on numbers of earthworm middens present and the soil hydraulic conductivity (rate of water infiltration). The data suggest two conclusions: (1) there exists a close positive relationship between earthworm activity and soil infiltration rate, and (2) if more than about one-third of the corn stover is removed, significant damage may be done to soil quality needed to sustain future production of crops and biofuels (see Section 20.6). Unfortunately, many models of potential biofuel production fail to take this relationship into account. The data are averages for three medium- to fine-textured soils under long-term no-till management in Ohio.* [Graphed from data in Blanco-Canqui et al. (2007)]

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BOX 11.1

GARDENERS' FRIEND NOT ALWAYS SO FRIENDLY[a]

Earthworms are legendary for the many ways they enhance the productivity of gardens, pastures, and croplands. However, in other ecological settings, "nature's tillers" can be quite damaging. In particular, these active immigrants are starting to wreak havoc in some of North America's forest ecosystems. Since the Pleistocene glaciers wiped out the native earthworms some 10,000 years ago, the plant–soil communities in these boreal forests have evolved without substantial earthworm populations. Without the soil-mixing action of earthworms, these forests have developed a thick, stratified forest floor, usually consisting of several distinct O horizons. This loose, thick litter layer is essential habitat for certain native plants (mayflowers, wood anemone, and trillium) and animals (millipedes, ground-nesting birds, and salamanders) (Figure 11.13).

Recently, scientists have observed that the forest floor has all but disappeared from certain boreal forest stands (Figure 11.14). They think they know the culprit—invading populations of *Lumbricus terrestris* and similar *anecic*-type earthworms. This type of earthworm is particularly damaging to the forest ecosystem for precisely the same actions that make it so beneficial in gardens and pastures—the incorporation of surface litter into the soil and production of deep vertical burrows. These actions rapidly destroy the forest floor O horizons and greatly accelerate the normally conservative cycling of nutrients.

Some of the worst impacts are being felt in Minnesota, USA, where European earthworms (including *Aporrectodea* sp., *Lumbricus rubellus*, and *L. terrestris*) have invaded the lake-dotted boreal forests. One approach to slowing the invasion of these uninvited soil engineers might be to surround the forest with buffer zones of habitat unsuitable for earthworms. Researchers believe the advance of these earthworms has been greatly abetted by their use as fishing bait. The take-home message: bring those bait worms home and dump them in your compost pile, not on the shore of your favorite fishing lake!

Figure 11.13 *Two native species threatened by earthworm invasion. Both the Polydesmida millipede (left) and the ringed salamander, Ambystoma annulatum (right) depend on a thick O horizon for habitat.* (Left photo courtesy of Ray R. Weil, right photo courtesy of Stan Trauth, Arkansas State University)

Figure 11.14 *Forest floor and upper soil horizons before (a and b) and after (c and d) invasion of Minnesota forest in the United States by exotic anecic earthworms. Note the thick O horizon of decomposed litter before (b), and its absence after (d) the earthworms did their work.* (University of Minnesota, David L. Hansen)

[a]For more on invasive earthworms, see Hendrix et al. (2008), Mendes et al. (2011), and Hopfensperger et al. (2011).

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cycling and aid plant growth also promote increased emissions of carbon dioxide and nitrous oxide, two major gases that drive global warming (see Sections 12.9 and 13.9). This mixed blessing of earthworm activity is illustrated by the data in Figure 11.11*c* where earthworm incorporation of plant litter substantially increased plant uptake of nitrogen, but also stimulated the loss of nitrogen as nitrous oxide gas. Results from dozens of similar mesocosm studies, as well as from a few field studies, around the world have provided a mixed picture. The presence of earthworms reduced greenhouse gas emissions in a few cases, but generally earthworm activity increased the global warming potential of soils by about 20%, mainly as a result of higher nitrous oxide emissions. There is too little information available to determine if the plant growth and soil quality enhancements by earthworms compensate for these increased gas emissions.

On balance, earthworms are usually very beneficial, and soil managers would do well to encourage their activity in most, but not all, situations.

Factors Affecting Earthworm Activity

Earthworms prefer cool, moist, but well-aerated soils well supplied with decomposable organic materials, preferably supplied as surface mulch. In temperate regions they are most active in the spring and fall, often curling into a tight ball (aestivating) to ride out hot, dry periods in summer. They do not live under anaerobic conditions. Most earthworms thrive best where the soil is not too acid (pH 5.5–8.5) and has an abundant supply of calcium (which is an important component of their mucilage excretions). Enchytraeid worms are much more tolerant of acid conditions and are more active than earthworms in some forested Spodosols. Most earthworms are quite sensitive to excess salinity.

Other factors that depress earthworm populations include predators (moles, mice, and certain mites and millipedes), very sandy soils (partly because of the abrasive effect of sharp sand grains), direct contact with ammonia fertilizer, application of certain insecticides (especially carbamates), and tillage. The last factor is often the overriding deterrent to earthworm populations in agricultural soils. Minimum tillage, with year-round vegetative cover and plenty of plant litter left as a mulch on the soil surface, is ideal for encouraging earthworms. The numbers commonly found in agricultural soils range from 0 to 300+ per square meter, the highest populations occurring in meadows, pastures, and under no-till rotations with cover crops. A simple method of assessing earthworm populations in grassland or arable soils is to dig into the surface soil to a depth of about 25–30 cm. During relatively cool, moist conditions, an average earthworm count of $100/m^2$ (about 5–10 per spade full) would indicate a good-sized population of these ecosystem engineers.

11.5 ANTS AND TERMITES[7]

Some mention has already been made (Section 11.2) of the varied food web roles of mesofauna arthropods (animals with a hard exoskeleton), namely, the mites (eight-legged arachnids, which account for about 30,000 soil-dwelling species) and the springtails (wingless insects in the order *Collembola*, of which some 6500 soil species are known). We will now turn focus on two groups of macrofauna insects, ants and termites, that are considered to be important ecosystem engineers.

Ants

Although historically somewhat ignored by soil ecologists, research increasingly points to ants' critical roles in soil function and impacts on the diversity both above- and belowground.

[6]A review of 237 observations from 57 published studies (Lubbers et al., 2013) showed that the presence of earthworms usually increased both CO_2 and N_2O gas emissions while having little effect on soil C accumulation.

[7]Ants are receiving increasing attention in the soil ecology literature (Anderson and Majer, 2004; Goheen and Palmer, 2010; Sanders and van Veen, 2011). Many descriptions of termite biology and ecological impacts are available (Ackerman et al., 2007; Eggleton, 2011; Sileshi et al., 2010).

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Nearly 9000 species of soil-inhabiting ants have been identified. They are most diverse in the humid tropics, but are perhaps most functionally prominent in temperate semiarid grasslands (Figure 2.31). Ants play important roles in forests from the tropics to the taiga. Some ant species act as detritivores, others as herbivores, and still others as predators.

A rather notorious example of the latter is the imported red fire ant (*Solenopsis invicta*), which arrived in the southeastern United States from South America in the 1940s and by the late 1990s had spread as far as California. Like many ants, the fire ant lives in large underground nests topped by mounds of soil about 30 cm tall. This ant is known for its painful, venomous bite (actually a combination of a nonvenomous bite followed by a venomous sting). As the fire ant destroys insect pests and weed seeds, in some situations it can actually benefit farmers' crops, but it is also known to physically damage many crops and to feed on beneficial native insects, soft-shelled eggs of native birds and reptiles, and even newborn mammals.

Some ants feed on the sugary fluid (*honeydew*) produced by aphids as these sucking insects attack vascular plants. The ants may "raise" the aphids in their nest or "herd" them while they feed on plant sap. Ants belonging to the genus *Formica* have been shown to offer forest trees significant relief from canopy-feeding aphids, a single nest of these ants collecting and devouring some 10 kg of aphids in a single summer. Ant nest–building activity can improve soil aeration, increase water infiltration (see Figure 6.16), and modify soil pH. The nests, and the microbial populations they encourage, also stimulate the cycling of soil nitrogen (Figure 11.15). Although ants occur widely and play vital and varied ecological roles, their cousins, the termites, have been much more intensively studied and will be considered next.

Termites

Termites live in complex social colonies found in about two-thirds of the world's land area (Figure 11.16). They are most prominent in the grasslands (savannas) and forests of tropical and subtropical areas (both humid and semiarid). Globally their activity is on a scale comparable to that of earthworms. In the drier tropics (less than 800 mm annual rainfall) termites surpass earthworms as the dominant soil fauna.

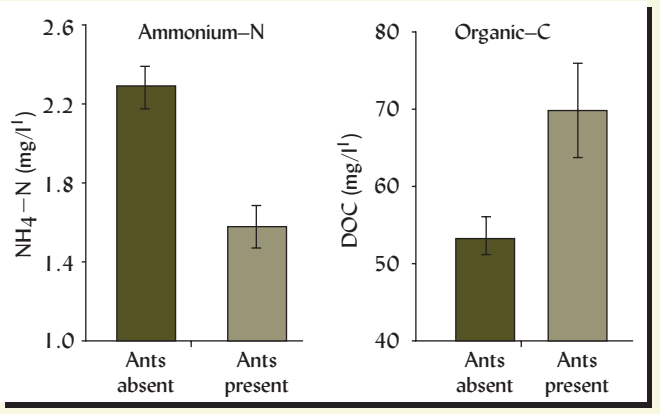

Figure 11.15 *Ants exert important direct and indirect influences on the soil ecosystem. (Left) The herbivorous harvester ant (Veromessor andrei) forages for plant material to bring back to its nests in semiarid grasslands. Studies have shown that the soil in its nests is enriched in mineral nutrients and supports higher and more diverse populations of bacteria, fungi, nematodes, and microarthropods compared to soil away from the ant nests. (Right) The predatory ant (Formica polyctena) influences the concentrations of ammonium-N and organic carbon in water leaching through O horizons in a Norway spruce forest. These measurements were made within a few cm of the tree trunks, where the ants tend to build their nests. The effects were not seen 30 cm away from the tree trunks. Ants belonging to this genus also protect both coniferous and deciduous trees by preying on leaf-eating insects in the tree canopies.* (© Alex Wild, used by permission)

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Figure 11.16 *Termites and ants in the humid tropics. (left) Predatory army ants (black) attack and overwhelm two soldier termites (brown) guarding a nest. (right) Soldier termites take up defensive positions inside their colony's mound in Liberia. Note the chambers in which fungi are cultivated and the soil particles glued together with termite saliva.* (Photos courtesy of Ray R. Weil)

Diversity and Diet. Termites are sometimes called *white ants*, although they are quite distinct from ants (one can distinguish an ant by its narrow "waist" between the abdomen and thorax; compare Figures 11.15 and 11.16*b*). There are thought to be about 3500 species of termites, most of which use cellulose in the form of plant fiber as their primary food. Yet most termites cannot themselves digest cellulose. Instead, many termites depend on a symbiosis with certain protozoa and bacteria living in their guts. These termite gut microorganisms produce the enzymes that degrade cellulose and allow the termite to derive energy from it. Termites (and their gut microorganisms) are major contributors to the breakdown of organic materials near or on the soil surface. The bacterial metabolism that takes place under anaerobic conditions in termite guts also accounts for a substantial fraction of the global production of methane (CH_4), an important greenhouse (global warming) gas (see Section 12.9).

Most termite species eat dead plant material (decaying logs, fallen leaves, etc.) but some attack the sound wood in standing trees. The latter groups have become quite infamous because of their habit of invading (and subsequently destroying) the houses people build of wood. The most damaging of the wood-eating species is the highly invasive Formosan subterranean termite (*Coptotermes formosanus*), which now infests wooden structures around the world in the tropical and subtropical zones. Most tree- and house-invading termites build protective tubes made of compacted soil and termite feces, which enable them to return to the soil for their daily water supply. Termite inspectors look for these earthen tunnels (about 1 cm in diameter) running up foundation walls under a house to indicate an infestation.

Mound-Building Activities. Termites are social animals that live in very complex labyrinths of nests, passages, and chambers that they build both below and above the soil surface. Termite mounds built from soil particles and feces cemented with saliva are characteristic features of many landscapes in Africa, Latin America, Australia, and Asia (Figure 11.17, *left*). These mounds are essentially termite "cities" with a network of underground passages and aboveground covered runways that typically spread 20–30 m beyond the mound. Several species, such as *Macrotermes spp*. in Africa, use their mounds to "cultivate" fungi which they feed with cellulose-rich plant materials. The fungi have the enzymes necessary to digest the cellulose and the termites then harvest and eat the fungi from these "gardens."

In building their mounds, termites transport soil from lower layers to the surface, thereby extensively mixing the soil and incorporating into it the plant residues they use as food. Scavenging a large area around each mound, these insects remove up to 4000 kg/ha of leaf and woody material annually, a substantial portion of the plant litter produced in many tropical ecosystems (Figure 11.17, *right*). They can also annually move more than 1000 kg/ha of soil in their mound-building activities. These activities have significant impacts on soil formation, as well as on current soil fertility and productivity.

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Figure 11.17 *Termites build nests above- and belowground and live in complex social colonies. (Left) A termite mound in a semiarid tropical savanna. The mound is constructed of subsoil material cemented hard with termite saliva. (Right) At the beginning of the rainy season, dozens of worker termites build funnel-shaped structures though which their colony mates—having grown wings—will exit their underground metropolis for migration.* (Photos courtesy of Ray R. Weil)

The quantity of soil materials incorporated into termite mounds can be enormous; up to 2.4 million kg/ha has been recorded (equivalent to a continuous soil layer about 20 cm deep). Depending on the species and environmental conditions, termites may build mounds 6 m or more in height and may extend them to an even greater depth into the soil in search of water or clay layers. Each mound can provide a home for 1 million termites. Certain species grow wings and migrate by air to form new colonies (Figure 11.17, *right*). The mounds may be abandoned after 10–20 years and can then be broken down by farmers to level the land for crop production. Attempts to level an occupied mound are usually frustrating, as the termites rebuild very rapidly unless the queen (egg-laying) termite is destroyed.

Effect of Termites on Soil Productivity. Termite effects on nutrient cycling and soil productivity are quite different from those of earthworms. While earthworms incorporate organic matter into the soil in a relatively uniform manner over a hectare of land, termites tend to create islands of fertility where they build their nests. The termites may mix plant residues into the soil of their nests, while denuding the soil surface of all plant litter (Figure 11.18). This termite behavior can make it extremely difficult to provide cropland with the protective benefits of a crop residue mulch.

Plant Growth on Termite Mound Material. Where the subsoil is richer in mineral nutrients than the topsoil or is rich in clay compared to a very sandy surface soil, the material from abandoned mounds may provide islands of relatively high plant production, due to greater availability of phosphorus, potassium, calcium, and moisture. On soils with a high water table, termite mounds may provide islands of better drainage and aeration that produce much better plant growth. In certain semiarid and savanna regions, the stable macrochannels constructed by termites greatly increase water infiltration into soils that otherwise tend to form impermeable surface crusts.

Plant growth on active mounds may be poor or absent (see Figure 11.17, *left*), however, once the termite mound is abandoned, the resulting "island" of soil high in clay, nutrients, and sometimes organic matter is often vegetated by a more diverse and vigorously growing plant community than exist on the nontermite affected part of the landscape (e.g., Figure 8.36). Even where the subsoil is poor in nutrients, the many years of plant litter incorporation often enhances the fertility of termite mound material. In some regions of sandy, infertile, droughty soils, farmers excavate the termite mound material and use it as a soil amendment to improve the productivity of their fields.

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Figure 11.18 *(Left) Termites in semiarid Texas, USA, prevent the accumulation of a plant litter mulch by rapidly covering plant debris with a coating of cemented soil and then incorporating the material into their nests. (Right) Individual worker termites (striped) drag cut pieces of leaves into their underground nest as soldier termites (large heads and mandibles) stand guard.* (Photos courtesy of Ray R. Weil)

11.6 SOIL MICROANIMALS[8]

From the viewpoint of microscopic animals, soils present many habitats that are essentially aquatic, at least intermittently so. For this reason the soil microfauna are closely related to the microfauna found in lakes and streams. The two groups exerting the greatest influence on soil processes are the nematodes and protozoa.

Nematodes

Nematodes—commonly called *threadworms* or *eelworms*—live in almost all soils, often in surprisingly great numbers (see Table 11.4) and diversity. Some 20,000 species have been identified of the 100,000 nematode species thought to exist. These unsegmented roundworms are highly mobile creatures about 4–100 μm in cross section and 40–1000 μm in length. They wriggle their way through the labyrinth of soil pores, sometimes swimming in water-filled pores (like their aquatic cousins), but more often pushing off the moist particle surfaces of partially air-filled pores. The latter mode of locomotion helps explain why some nematodes are active and reproduce when the soil water potential is so low (see Section 5.4) that only pores smaller than 1 μm (far too small for nematodes to enter) are filled with water. Nematodes are very sensitive to soil water content and porosity. Moist, well-aggregated, or sandy soils typically have especially high nematode populations, as these soils contain abundant pores large enough to accommodate their movements. When the soil becomes too dry, nematodes survive by coiling up into a **cryptobiotic** or resting state, in which they seem to be nearly impervious to environmental conditions and use no detectable oxygen for respiration. In semiarid rangelands, nematode activity has been shown to be largely restricted to the first few days after each rainfall that awakens the nematodes from their cryptobiotic state.

Feeding Habits. Most nematodes feed on fungi, bacteria, and algae or prey on other soil animals. Perhaps 10–20% of the nematodes in most soil are primary consumers that feed on liv-

[8]For an illustrated overview of the roles of nematodes and protozoa in soil fertility, see Hoorman (2011). For a more detailed discussion of soil nematode ecology, see Neher (2010).

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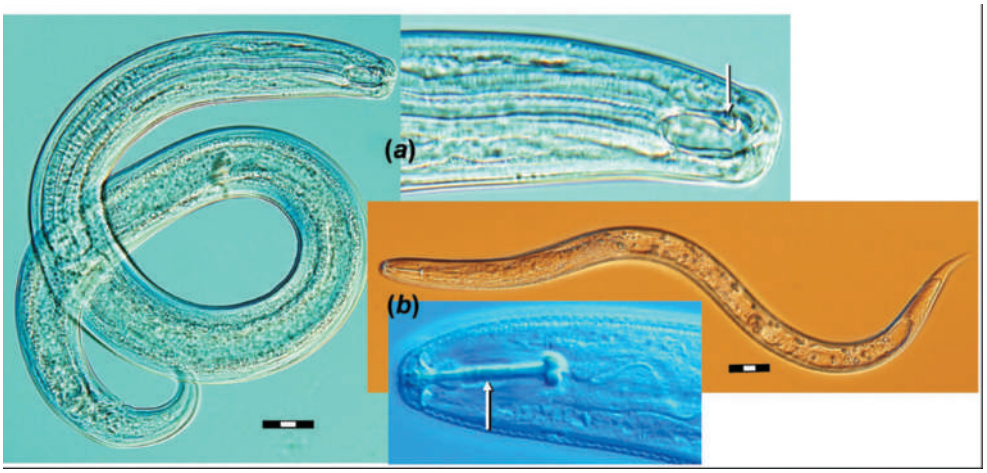

Figure 11.19 *A predator nematode (a, Mononchidae) and a plant root parasite (b, soybean cyst nematode). The head and mouth parts of a nematode often reflect its trophic role, as the inset enlargements of these nematodes illustrate. Predators usually have hard teeth (a, arrow) and a large mouth for capturing and swallowing prey. Nematodes that feed on plant roots or fungal hyphae have a retractable spearlike mouth part (b, arrow) that pierces the targeted cell to feed on the liquid contents. Scale bars marked in 10 μm units.* (Photo courtesy of Joel Gruver, Western Illinois University)

ing plants. The different trophic groups of nematodes can often be distinguished by the type of mouth parts present (Figures 11.19 and 11.20). Grazing by nematodes can have a marked effect on the growth and activities of fungal and bacterial populations; much like a fruit tree is affected by pruning, the microbial activity can be stimulated by light grazing or reduced by heavy grazing. Since bacterial cells contain more nitrogen than the nematodes can use, microbial-feeding nematodes excrete considerable soluble nitrogen. This nematode activity accounts for 30–40% of the plant available nitrogen released in some ecosystems.

Predatory nematodes, like wolves or lions aboveground, can have a major "top-down" influence on the whole food web community. Unlike most aboveground predators, most predatory nematodes are not larger than their prey—probably because the predators must be able to squeeze into the same small soil pores in which the prey is hiding. The prey can include other nematodes, protozoa, or insect larvae. In fact, nematodes that kill the larvae of insect pests in the soil are sold for use as biological control agents, an environmentally beneficial alternative to the use of toxic pesticides. These nematodes that attack insect larvae carry symbiotic (to the nematode) bacteria to kill the much larger insect by disease—hence these nematodes are referred to as entomopathogenic (insect disease causing). Once established, they can provide effective, long-term control of such soilborne insect pests as the corn rootworm or the grubs (Japanese beetle larvae) that destroy homeowners' lawns (Figure 11.21).

Plant Parasites. Some nematodes, especially those of the genus *Heterodera*, can infest the roots of practically all plant species by piercing the plant cells with a sharp, spearlike mouth

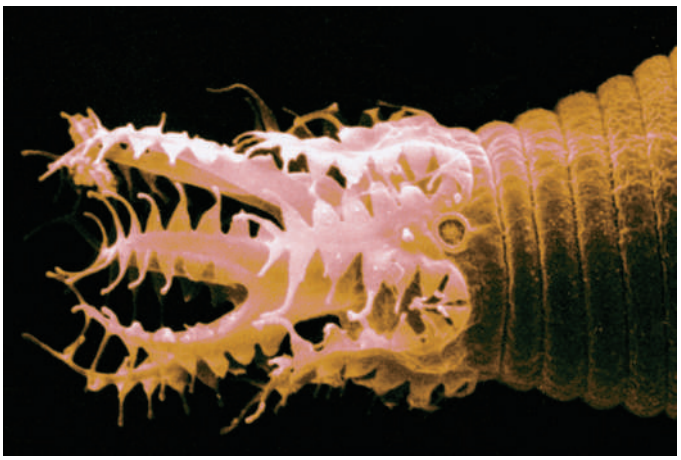

Figure 11.20 *Head of bacteria feeding nematode (Acrobeles ciliates). The ornate structures act as lips and swirl around during feeding to sweep bacteria into the mouth.* (Photo courtesy of Sven Boström, Swedish Museum of Natural History)

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Figure 11.21 *Nematodes feeding inside an insect larva. These nematodes are entomopathogenic—a few nematodes invade the insect larvae, carrying bacteria that cause the larvae to quickly die of disease while the nematodes reproduce, multiply, and eat both the bacteria and the insect tissue. After a week or so, the insect larva has been consumed and the horde of new nematodes and their bacterial allies return to the soil from the insect and search for a new victim.* (Yi Wang & Randy Gaugler)

part. These wounds often allow infection by secondary pathogens and may cause the formation of knotlike growths on the roots. Minor nematode infestations are nearly ubiquitous and often have little deleterious effect on the host plant. In fact, low levels of root feeding may even stimulate greater root growth and plant health. However, infestations beyond a certain threshold level result in serious stunting of the plant. Cyst- (egg-sac-) forming nematodes are major pests of soybeans, while root-knot-forming nematodes cause widespread damage to fruit trees and solanaceous crops (Figure 11.22).

Until recently, the principal methods of controlling crop damaging nematodes were long rotations with nonhost crops (often five years is required for the parasitic nematode

Figure 11.22 *(Left) The stunted (foreground) and large (background) tobacco plants pictured both received identical management. (Right) Examination of the root systems of the stunted plant showed that it was heavily infested with root-knot nematodes, which stunted the roots and produced knotlike deformities.* (Photos courtesy of Ray R. Weil)

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populations to sufficiently dwindle), use of genetically resistant crop varieties, and soil fumigation with highly toxic chemicals (**nematicides**). The use of soil nematicides, such as methyl bromide, has been sharply restricted because of undesirable environmental effects.

New, less dangerous approaches to nematode control include the use of hardwood bark for containerized plants and interplanting or rotating susceptible crops with plants such as marigolds that produce root exudates with nematicidal properties (Figure 11.23). Certain plants in the Brassicaceae family (such as mustards, radishes, and rapeseed) contain sulfurous compounds called glucosinolates. When the residues of these plants break down in the soil, their glucosinolates produce volatile biofumigants that can kill certain nematodes. The use of these plants as green manures has successfully substituted for the use of more broadly toxic synthetic chemicals to control nematodes in potato, strawberry, and other nematode-sensitive crops. Progress has also been made in the development of nematode-resistant varieties of such plants as soybeans. Individually, each of these measures may provide only partial crop protection, but when applied together, such protective measures can be highly effective.

Protozoa

Protozoa are mobile, single-celled creatures that capture and engulf their food. With some 50,000 species in existence, they are the most varied and numerous microfauna in most soils (Table 11.4). Most are considerably larger than bacteria (see Figure 11.1), having a diameter range of 4–250 μm. Their cells do not have true cell walls and have a distinctly more complex organization than bacterial cells. Soil protozoa include amoebas (which move by extending and contracting pseudopodia), ciliates (which move by waving hairlike structures; see Figure 11.24), and flagellates (which move by waving a whiplike appendage called a *flagellum*). They swim about in the water-filled pores and water films in the soil and can form resistant resting stages (called *cysts*) when the soil dries out or food becomes scarce.

Sometimes as many as 40 or 50 different protozoa species may occur in a single sample of soil. The liveweight of protozoa in surface soil ranges from 20 to 200 kg/ha (see Table 11.4). A considerable number of serious animal and human diseases are attributed to infection by protozoa, but mainly by those that are waterborne, rather than soilborne. Most soil-inhabiting protozoa prey upon soil bacteria, exerting a significant influence on bacterial populations and decomposition pathways in soils.

Protozoa generally thrive best in moist but well-aerated soils and are most numerous in surface horizons. Protozoa are especially active in the area immediately around plant roots. Their main influence on organic matter decay and nutrient release is through

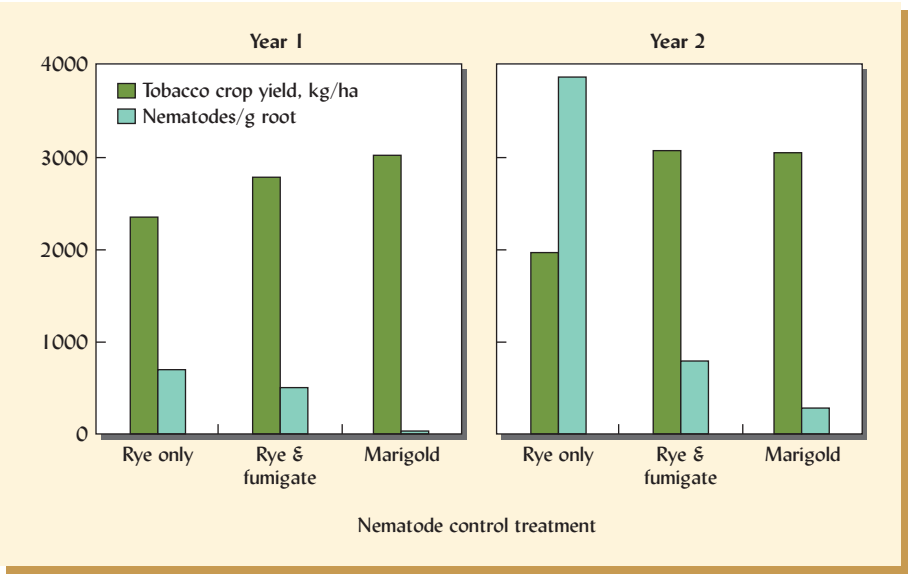

Figure 11.23 *Marigolds control plant-parasitic nematodes. A susceptible host plant (tobacco) was grown in the summers of years 1 and 2 on a sandy soil in Ontario, Canada. The untreated plots (rye only) and fumigated plots (rye and fumigate) were cover cropped with rye each winter. The fumigated plots were injected in years 1 and 2 with a chemical fumigant (1,3-dichloropropene). The remaining plots (marigold) were planted to marigolds (Tagetes patula cv. "Creole") only in the summer of the year before the susceptible crop was first planted. The nematode infestation grew worse in the second year that a susceptible crop was grown (especially in rye only plots) and without nematode control the crop yield declined substantially. Growing marigolds in one year controlled nematodes in susceptible crops for the following two years.* [Based on data from Reynolds et al. (2000); used with permission of the American Society of Agronomy]

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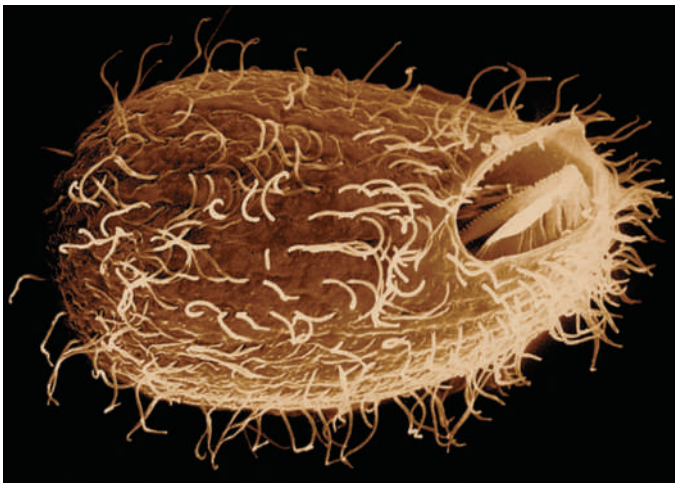

Figure 11.24 *A ciliated protozoan (Glaucoma scintillans), one of the types of microanimals found in soils. Predation by protozoa exerts a major influence on the abundance, diversity, and activity of soil bacteria.* (Susan Corliss Kinkley)

their effects on bacterial populations. In pursuit of their bacterial prey, some soil-dwelling protozoa are adapted to squeezing into soil pores with openings as small as 10 μm. Still, soil aggregates often provide even smaller pores where bacterial cells can hide to escape predation. This protection from protozoa predation is a characteristic of the soil environment that helps explain the greater diversity of bacteria in soils than in aquatic habitats where such hiding places do not exist.

Other Fascinating Soil Microcreatures

Space limitations do not allow us to describe in detail the many other invertebrate animals of the soil, such as the hundreds of species of **rotifers** (somewhat like zooplankton of the soil water) and **tardigrades** (sometimes called water bears for their teddybear-like appearance), most of which are smaller than 1 mm and either prey on protozoa or feed on fungi, algae, and bacteria. However, one soil life-form is simply too fascinating to omit: the ***Dictyostelium* slime mold**. These amoeba-like, eukaryotic single-celled microorganisms live in the litter layers and the upper few centimeters of soil, feeding on bacteria, much as protozoa do. However, when the local food supply runs out, a truly amazing phenomenon occurs that is illustrative of the degree to which soil organisms often act together. The individual ***Dictyostelium*** amoeboid cells begin to congregate. In response to a complex pattern of chemical signals, some 50,000 of these individual organisms stream together to form a mound about 0.1 mm in size. The cells in this mound then differentiate themselves into two types, most conglomerating together to form a "foot," while the others form a kind of "head"—the 50,000 cells now behaving as a single, multicellular organism! This tiny "creature" crawls, slug-like, up to the soil surface, where the cells undergo yet another rearrangement. The cells of the slug's "foot" transform into the stalk of a fruiting body, atop which the slug's "head" transforms into spores—which can now disperse through the air to new hunting grounds.

11.7 PLANT ROOTS[9]

Green plants store the sun's energy and are the primary producers of organic matter (see Figure 11.3). Their roots grow and die in the soil and are considered as soil organisms in this text. They typically occupy about 1% of the soil volume and may be responsible for a quarter to a third of the respiration occurring in a soil. Roots usually compete for oxygen, but they also supply much of the carbon and energy needed by the soil community of fauna and

[9]For a complete scientific review of all aspects of roots and their soil interactions, see Eshel and Beeckman (2013).

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microbes. The activities of plant roots greatly influence soil chemical and physical properties, the specific effects depending on the type of soil and plant in question (see, e.g., Section 7.8). As we shall see, plant roots interact with other soil organisms in varied and complex ways.

Root Morphology

Depending on their size, roots may be considered to be either meso- or microorganisms. Fine feeder roots range in diameter from 100 to 400 μm, while root hairs are only 10–50 μm in diameter—similar in size to the strands of microscopic fungi (see Figure 11.1). The arrangement of major root tissues may be likened to a cylinder within a cylinder, the outer cylinder of loosely arranged cells being the cortex and the inner cylinder more tightly packed cells being the stele. The stele contains the plant's plumbing system of xylem tubes for water and nutrient uptake and phloem tubes for two-way redistribution of plant chemicals. Certain cells in the root's outer skin, the epidermis, can elongate to form long, thin protuberances termed root hairs (Figures 11.25 and 1.29). One function of root hairs is to anchor the root as it pushes its way through the soil. Other functions are to maintain direct contact with soil particle and water films and to increase the amount of root surface area available to absorb water and nutrients from the soil solution.

Roots grow by forming and expanding new cells at the growing point (meristem), which is located just behind the root tip. This growing point can exert surprisingly high pressures to enable it to push ahead through the soil; generally thicker roots can exert greater pressures than thin ones. To lubricate the root's push through the soil, certain cells near the tip exude a nonwater soluble gel-like substance termed **mucigel**. The root tip itself is shielded by a protective cap of expendable cells that slough off as the root pushes through the soil, leaving a trail of broken cells imbedded in the mucigel coating, the combination of which both attracts and provides food sources to throngs of mainly beneficial microorganisms (Figure 11.25).

Root morphology is affected by both type of plant and soil conditions. For example, fine roots may proliferate in localized areas of high nutrient concentrations. Root-hair formation is stimulated by contact with soil particles and by low nutrient supply. When soil water (or nutrient supply) is scarce, plants typically put more energy into root growth than into shoot growth, decreasing the shoot-to-root ratio—thus increasing the uptake of water and minimizing its loss by transpiration. Roots may become thick and stubby in response to high soil bulk density or high aluminum concentrations in soil solution (see Sections 4.7 and 9.7).

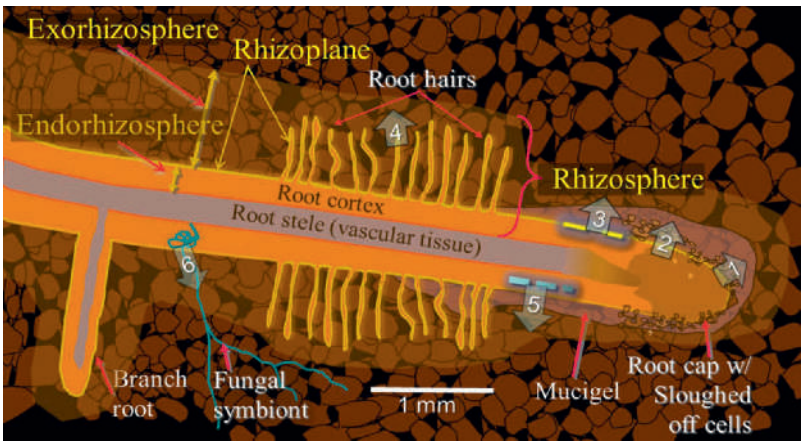

Figure 11.25 *Diagram of a root showing the rhizosphere (light brown shaded area) and its three zones: the endorhizosphere consisting of the root cortex where the solution is in contact with the soil solution, the exorhizosphere consisting of the soil in the immediate vicinity of the root and profoundly under its influence, and the rhizoplane consisting of the outer surface of the root including its root hairs. Six ways that roots add organic compounds to the rhizosphere are also shown (broad numbered arrows): (1) sloughing off of root cap cells; (2) excretion of mucigel; (3) spilling of cell contents when epidermal cells are lysed (broken); (4) exudation of specific compounds produced by root hairs; (5) exudation of various compounds by cortical cells; (6) export of organic compounds to symbiotic fungi (see Section 11.9).* [Diagram courtesy of Ray R. Weil]

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How Roots Alter Soil Conditions

Roots physically, chemically, and biologically modify the soil they live in. Physically, roots alter the arrangement of particles, widening some porespaces and creating new channels as they push through the soil. Roots follow paths of least resistance, growing between soil peds and into existing cracks and channels. Once extended into a pore, the root matures and expands, exerting lateral forces that enlarge that pore while compressing the soil around it. Roots also encourage soil shrinkage and cracking by removing moisture from the soil. This action, along with the chemical and biological effects discussed next, increases stable soil aggregation.

Roots chemically alter the soil around them by what they take out it (depletion of nutrients and water) and what they put into it (root exudates and tissues). Root exudates help to further stabilize soil aggregates, both directly and indirectly by supporting a myriad of fungi and bacteria. In addition, when roots die and decompose, they provide input to soil organic matter, not only in the A horizon, but also throughout the soil profile. If soil conditions permit, the roots of annual herbaceous plants (such as most crops) send their roots down 1–2 m. Perennial plants, especially woody species, may send some roots more than 5 m deep if restricting layers are not encountered. Generally, rooting is deepest in hot, dry climates and most shallow in boreal or wet tropical environments (see Figure 5.44).

The importance of root residues in helping to maintain soil organic matter levels is often overlooked, even though root contributions are generally more important than the more visible (to humans) aboveground plant residues. In grasslands, about 50–60% of the net primary production (total plant biomass) is commonly in the roots. In addition, grass fires may remove most of the aboveground biomass, so that the deep, dense root systems are the main source of organic matter added to these soils. In forests, 40–70% of the total biomass production may be in the form of tree roots. In arable soils, the mass of roots remaining in the soil after crop harvest is commonly 15–40% that of the aboveground crop. If an average figure of 25% is used, good crops of oats, corn, and sugarcane would be expected to leave about 2500, 4500, and 8500 kg/ha of root residues, respectively. When considering the contribution of a relatively young cover crop plants (Section 16.2), it should be remembered that in the early stages of development, plants give priority to roots, so the biomass below ground may be much greater than the biomass above ground. The mass of organic compounds contributed by roots is seen to be even greater when the rhizosphere effects discussed in the following subsections are considered.

Rhizosphere[10]

The zone of soil significantly influenced by living roots is termed the **rhizosphere** and extends out to about 2–3 mm from the root surface (Figures 1.29 and 11.25). The entire rhizosphere is sometimes considered to include three zones: (1) the **endorhizosphere** consisting of the root cortex where the cells are loosely packed and the intercellular spaces are filled with an extension of the soil solution and easily colonized by soil bacteria, (2) the **rhizoplane** consisting of the outer surface of the root including its root hairs adhering soil, and (3) the **extorhizosphere** consisting of the soil close enough to the root to be profoundly under its influence. The chemical and biological characteristics of the extorhizosphere can be very different from those of the bulk soil. Soil acidity is commonly ten times (1 pH unit) higher or lower in the rhizosphere than in the bulk soil (e.g., see Figure 9.13). Roots greatly affect the nutrient supply in this zone. On one hand roots withdraw dissolved nutrients and so deplete this zone. On the other hand, roots exude compounds that hasten the release of nutrients from soil minerals and organic matter. By these and other means, roots affect the mineral nutrition of soil microbes, just as the microbes affect the nutrients available to the plant roots.

Rhizodeposition

Roots add organic compounds to the rhizosphere in at least six ways (see broad numbered arrows in Figure 11.25): (1) cells from the root cap and epidermis continually slough off as the

[10]For a well-illustrated basic introduction to the rhizosphere with insights only an expert could provide, see McNear Jr. (2013).

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root grows and enrich the rhizosphere with a wide variety of cell contents; (2) cells near the root tip excrete large quantities of a nonwater soluble mucilage gel (mucigel); (3) epidermal cells are lysed (broken) by friction or microbial attack and spill their cell contents into the adjacent soil; (4) epidermal cells, including root hairs, actively produce and exude specific compounds; (5) cortical cells passively leak—or in some cases actively exude—a wide variety of plant metabolites; and (6) certain cortical cells export organic compounds directly to symbiotic fungi.

Young roots are most active in exuding organic compounds into the rhizosphere. The exuded chemicals include a myriad of low-molecular-weight organic compounds such as organic acids, sugars, amino acids, and phenolic compounds. Many of these compounds serve as substrate for beneficial microbes with which the plants have evolved symbiotic relationships. Many of the organic acids serve to enhance the availability of plant nutrients in the rhizosphere (see Section 15.8). Some of the root exudates, especially the phenolics, exert growth-regulating influences on other plants and soil microorganisms in a phenomenon called **allelopathy** (see Section 12.5). Other compounds serve as chemical signals by which the plant root communicates with other roots or microbes, attracting friends (see Figure 11.26 for an example), repelling foes, or even warning future generations of hazards encountered.

The high-molecular-weight mucilages secreted by root-cap cells and epidermal cells near apical zones form a substance called **mucigel** when mixed with microbial cells and clay particles. Mucigel appears to have several beneficial functions: It lubricates the root's movement through the soil; it improves root–soil contact, especially in dry soils when roots may shrink in size and lose direct contact with the soil (see Figure 5.46); its high polysaccharide content helps stabilize soil aggregates thus improving the physical conditions for both root and microbial growth; it may protect the root from certain toxic chemicals in the soils; and its agar-like properties provide an ideal environment for the growth of the rhizosphere microorganisms.

Taken together with the constant death and decay of older roots, these types of chemical additions to the soil are termed **rhizodeposition** and typically account for 2–30% of total dry-matter production in young plants. The roots of common grain and vegetable plants have been observed to rhizodeposit 5–40% of the organic substances translocated to them from the plant shoot. Sometimes when a plant is carefully uprooted from a loose soil, these root exudates cause a thin layer of soil, approximating the rhizosphere, to form a sheath around the actively growing root tips (Figure 11.27). Because older roots are constantly dying and new roots constantly growing, the amount of organic material deposited in the rhizosphere during the growing season of annual plants may be more than twice the amount remaining in the root system at the end of the growing season. Rhizodeposition decreases with plant age but increases with soil stresses, such as compaction and low nutrient supply.

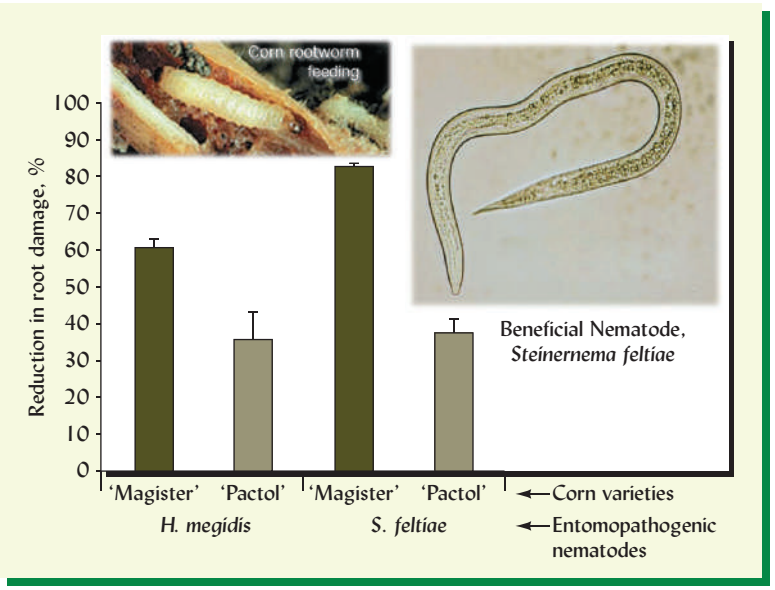

Figure 11.26 *Example of signaling compound rhizodeposition. The Western corn rootworm (Diabrotica virgifera) feeds on corn roots and severely damages this major food crop in many parts of the world. As a defense, roots of some corn plants can release a volatile chemical ((E)-b-caryophyllene) when they first suffer damage from this insect larvae pest. This signaling compound diffuses into the soil and specifically "recruits" certain entomopathogenic nematodes (Figure 11.21) that can attack and kill corn rootworms. However, the ability to release this signaling compound has been inadvertently lost from many high yielding corn hybrids. Such nonsignaling hybrids get less help from nematodes and are more reliant on pesticides to minimize corn root worm damage. Under field conditions the beneficial nematodes H. megidis and S. feltiae reduced root worm damage much more effectively on a corn variety ("Megister") that produces the below-ground signal than on a variety ("Pactol") that does not (bar graph).* (Prof. Jarmo Holopainen)

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Figure 11.27 *The rhizosphere is greatly enriched in organic compounds excreted by the roots. These exudates and the microorganisms they support, as well as root hairs, have caused the rhizosphere soil to adhere to these grass roots as a sheath, except near the root tips where the bare white root is visible. The soil is a sandy loam.* (Photo courtesy of Ray R. Weil)

Because of the rhizodeposition of carbon substrates and specific growth factors (such as vitamins and amino acids), microbial numbers in the rhizosphere are typically 2–10 times as great as in the bulk soil (sometimes expressed as a *R/S ratio*). This effect and processes just described explain why plant roots are among the most important organisms in the soil ecosystem.

11.8 SOIL ALGAE

Like higher plants, algae consist of eukaryotic cells, those with nuclei organized inside a nuclear membrane. (Organisms formerly called *blue-green algae* are prokaryotes and therefore will be considered with the bacteria.) Also like higher plants, algae are equipped with chlorophyll, enabling them to carry out photosynthesis. As photoautotrophs, algae need light and are therefore mostly found very near the surface of the soil. Some species can also function as heterotrophs in the dark. A few species are photoheterotrophs that use sunlight for energy but cannot synthesize all of the organic molecules they require (see Table 11.3).

Most soil algae range in size from 2 to 20 μm. Many algal species are motile and swim about in soil pore water, some by means of flagella (whip-like "tails"). Most grow best under moist to wet conditions, but some are also very important in hot or cold desert environments. Sometimes the growth of algae may be so great that the soil surface is covered with a green or orange algal mat. Some algae (as well as certain cyanobacteria) form *lichens*, symbiotic associations with fungi. These are important in colonizing bare rock and other low-organic-matter environments (see Figure 2.8). In unvegetated patches in deserts, algae commonly contribute to the formation of **microbiotic crusts** (see Section 11.14).

Several hundred species of algae have been isolated from soils, but a small number of species are the most prominent in soils throughout the world. The mass of these live algae may range from 10 to 500 kg/ha (see Table 11.4). In addition to producing a substantial amount of organic matter in some fertile soils, certain algae excrete polysaccharides that have strong favorable effects on soil aggregation (see Section 4.5).

11.9 SOIL FUNGI[11]

Soil fungi comprise an extremely diverse group of microorganisms. Tens of thousands of species have been identified in soils, representing some 170 genera. As many as 2500 species have been reported to occur in a single location. Scientists, using DNA and fatty acids extracted

[11]For an in-depth but accessible and well-illustrated book on everything fungi—from ecological roles to how to grow them as culinary delights, see Stamets (2005).

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from soils, estimate that there are at least 1 million fungal species in the soil still awaiting discovery. Because of the extensive filamentous morphology of many fungi, it is difficult to define the numbers of fungi in soil. For example, soil scientists applying DNA molecular analysis techniques determined that the fungal strands permeating the soil and tree roots of an entire 20-hectare forest stand belonged to *a single organism* that weighed more than 10,000 kg and was over 1500 years old! Instead of counting numbers, scientists use the biomass or hyphal length per m^2 as more meaningful measures of fungal presence. Total fungal biomass typically ranges from 1000 to 15,000 kg/ha in the upper 15 cm (Table 11.4). The fungi commonly dominate soil biomass, exceeding even that of the bacteria.

Fungi are eukaryotes with a nuclear membrane and cell walls. Biochemically and genetically they are more closely related to us humans than they are to such other microorganisms as bacteria or archaea. As heterotrophs, they depend on living or dead organic materials for both their carbon and their energy. Fungi are aerobic organisms, although some can tolerate the rather low oxygen concentrations and high levels of carbon dioxide found in wet or compacted soils. Strictly speaking, fungi are not entirely microscopic, since some of these organisms, such as mushrooms, form macroscopic structures that can easily be seen without magnification.

For convenience of discussion, fungi may be divided into three groups: (1) yeasts, (2) molds, and (3) mushroom fungi. *Yeasts*, which are single-celled organisms, live principally in waterlogged, anaerobic soils. *Molds* and *mushroom fungi* are both considered to be filamentous fungi, because they are characterized by long, threadlike, branching chains of cells. Individual fungal filaments, called **hyphae** (Figure 11.28), are often twisted together to form **mycelia** that appear somewhat like woven ropes. Fungal mycelia are often visible as thin, white or colored strands running through decaying plant litter (Figure 11.29). Filamentous fungi reproduce by means of spores, often formed on fruiting bodies, which may be microscopic (e.g., molds, Figure 11.28) or macroscopic (such as that shown in Figures 11.30 and 11.31).

Molds

The molds are distinctly filamentous, microscopic, or semimacroscopic fungi that play a much more important role in soil organic matter breakdown than the mushroom fungi. Molds develop vigorously in acid, neutral, or alkaline soils. Some are favored, rather than harmed, by lowered pH. Consequently, they may dominate the microbes in acid surface soils, where bacteria and actinomycetes offer only mild competition.

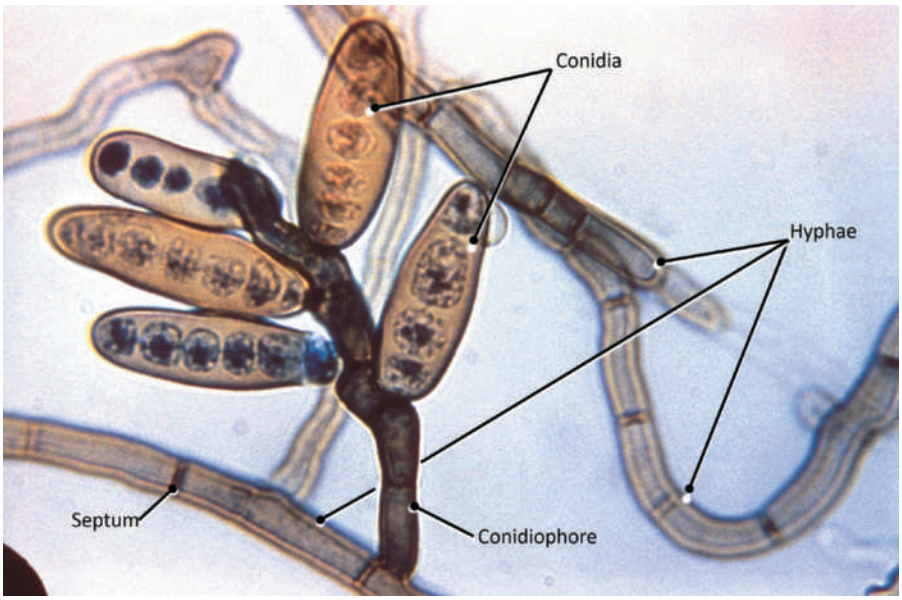

Figure 11.28 *A highly magnified soil fungus in the genus Helminthosporium, showing the long chains of cells called hyphae as well as a reproductive structure termed a conidiophore. The septa that separate the cells of the hyphae are clearly visible, as are the five multicellular fruiting bodies or conidia attached to the conidiophore.* (Photo by Hardin, courtesy of U.S. Department of Health and Human Services, Centers for Disease Control and Prevention)

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Figure 11.29 *White rot fungi include many species of Basidiomycota and are known for their ability to produce enzymes that breakdown lignin, cellulose and hemicellulose. These fungi are able to metabolize materials that most microorganism cannot, including woody debris in forests. Fortunately, their extracellular enzymes are not specific for lignin, but can also be put to work cleaning up soils contaminated by other complex aromatic compounds such as synthetic dyes and pesticides. (Left) Fruiting bodies of white rot fungi decomposing a fallen tree trunk. (Right) Fruiting bodies of a Bird's Nest fungus (Cyathus sp.) contain disc-shaped spores ("eggs") that are scattered forcefully when the cone is hit by a raindrop. Like other white rot fungi, this fungus produces enzymes that easily break down such woody materials as forest litter or corncobs left on agricultural fields after harvest. Individual "nests" are about 1 cm in diameter.* (Photos courtesy of Ray R. Weil)

Figure 11.30 *White rot fungi include many species of Basidiomycota and are known for their ability to produce enzymes that breakdown lignin, cellulose and hemicellulose. These fungi are able to metabolize materials that most microorganism cannot, including woody debris in forests. Fortunately, their extracellular enzymes are not specific for lignin, but can also be put to work cleaning up soils contaminated by other complex aromatic compounds such as synthetic dyes and pesticides.* (Left) *Fruiting bodies of white rot fungi decomposing a fallen tree trunk.* (Right) *Fruiting bodies of a Bird's Nest fungus* (Cyathus sp.) *contain disc-shaped spores ("eggs") that are scattered forcefully when the cone is hit by a raindrop. Like other white rot fungi, this fungus produces enzymes that easily break down such woody materials as forest litter or corncobs left on agricultural fields after harvest. Individual "nests" are about 1 cm in diameter.* (Photos courtesy of Ray R. Weil)

Many genera of molds are found in soils. Four of the most common are *Penicillium*, *Mucor*, *Fusarium*, and *Aspergillus*. The complexity of the organic compounds available as food seems to determine which particular mold (or molds) prevail. Their biomass fluctuates greatly with soil conditions. In some cases much of the hyphal length measured may no longer be living.

Mushroom Fungi

These fungi are associated with forest and grassland vegetation where moisture and organic residues are ample. Although the mushrooms of many species are extremely poisonous to humans, some are edible—and a few have been domesticated and are grown as popular food items.

The aboveground fruiting body of most mushrooms is only a small part of the total organism. An extensive network of hyphae permeates the underlying soil or organic residue. While mushrooms are not as widely distributed as the molds, these fungi are very important,

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especially in the breakdown of woody tissue, and because some species form a symbiotic relationship with plant roots (see "Mycorrhizae," following).

Activities of Fungi

As saprophytes decomposing organic materials in soil, fungi are the most versatile and persistent of any group. Cellulose, starch, gums, and lignin, as well as the more easily metabolized proteins and sugars, succumb to their attack. Otherwise resistant materials such a wood (lignin) and cellulose and even complex synthetic ring-structured compounds are rapidly broken down a group of fungi termed **white rot fungi** (Figure 11.30) because of the whitish residue and mycelial growth that mark their decay. Fungi play major roles in the formation and stabilization of soil organic matter (see Section 12.4) and soil aggregates (see Section 4.5). The ability of fungi to tolerate low pH is especially important in decomposing organic residues in acid forest soils. Their ability to grow mycelia out from the soil allows them to dominate decomposition in surface litter both in forests and in no-till agricultural fields.

Fungi are quite efficient in using the organic materials they metabolize. Up to 50% of the substances decomposed by fungi may become fungal tissue, compared to about 20% for bacteria. Soil *fertility* depends in no small degree on nutrient cycling by fungi, since they continue to decompose complex organic materials after most bacteria and actinomycetes have essentially ceased to function. Soil *tilth* also benefits from fungi as their hyphae stabilize soil structure (see Box 4.4 and Figure 4.15). Some of the nutrient cycling and ecological activities of soil fungi are made easily visible in the case of "fairy rings," commonly seen on lawns and pastures in early spring (Figure 11.31).

In addition to the processing of organic residues and cycling of nutrients, numerous other fungal activities have significant impact on soil ecology. A few species even trap and consume nematodes (see Figure 11.32). Soil fungi can synthesize a wide range of complex organic compounds in addition to those associated with soil humus. Certain fungi produce compounds that kill other fungi or bacteria and provide a competitive edge over rival microorganisms in the soil. These fungi have proved to be highly beneficial to human society (see Sections 11.10 and 11.14).

Unfortunately, not all the compounds produced by soil fungi benefit humans or higher plants. A few fungi produce chemicals (**mycotoxins**) that are highly toxic to plants or animals

Figure 11.31 *A "fairy ring" of fungal growth (a) and the fungi's fruiting bodies (mushrooms) (b,c). As the fungi (most commonly Marasmius spp.) metabolize grass thatch and residues, they release excess nitrogen that stimulates the lush green growth of the grass, which is especially visible in early spring. Later, bacteria decompose the aging and dead fungi, producing a second release of nitrogen. The fungus produces a chemical that is toxic to itself. Therefore, each generation must grow into uncolonized soil, producing an ever-expanding circle of fungi and decay marked by an ever-larger ring of dark green grass. The grass in the center of the ring is often water-stressed because the fungi render the upper soil layers somewhat hydrophobic.* (Photos courtesy of Ray R. Weil)

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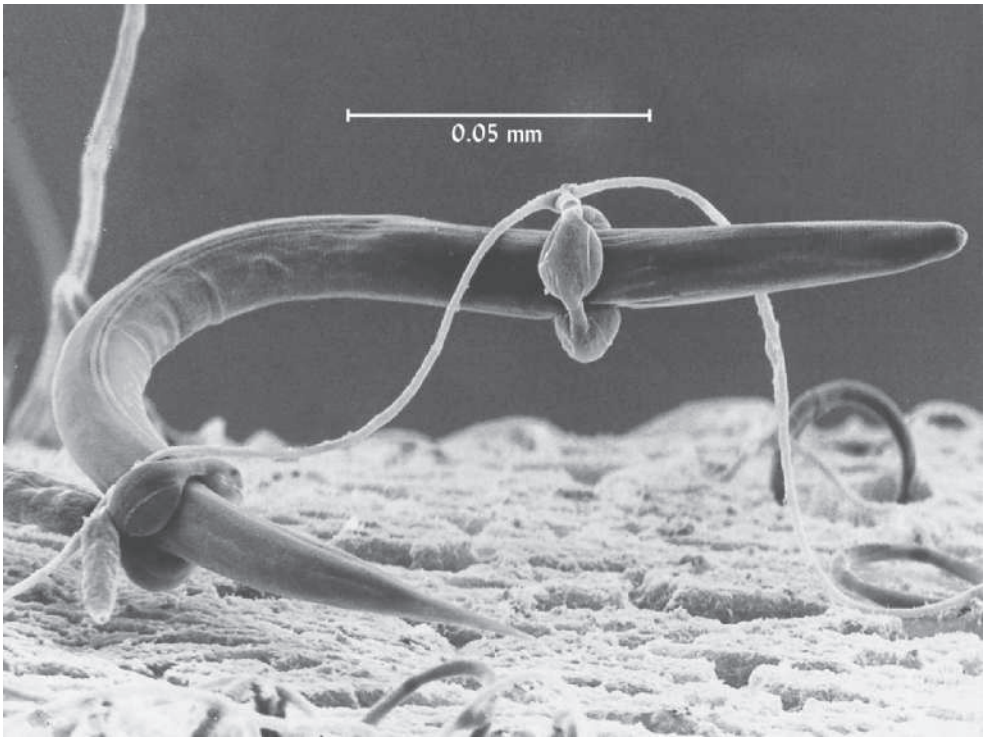

Figure 11.32 *Several species of fungi prey on soil nematodes—often on those nematodes that parasitize higher plants. Some species of nematode-killing fungi attach themselves to, and slowly digest, the nematodes. Others, like this Arthrobotrys anchonia, make loops with their hyphae and wait for a nematode to swim through these lasso-like structures. The loop is then constricted, and the nematode is trapped. The nematode shown here is being crushed by two such fungal loops. Additional loops can be seen in their nonconstricted configuration.*
(Photo courtesy of George L. Barron, University of Guelph)

(including humans). An important example of the latter is the production of highly carcinogenic aflatoxin by the fungus *Aspergillus flavus* growing on seed crops such as corn or peanuts, especially when the seeds are exposed to soil and moisture. Other fungi produce compounds that allow them to invade the tissues of higher plants (see Section 11.13), causing such serious plant diseases as wilts (e.g., *Verticillium*) and root rots (e.g., *Rhizoctonia*).

On the other hand, efforts are now underway to develop the potential of certain fungi (such as *Beauveria*) as biological control agents against some insects and mites that damage higher plants. These examples merely hint at the impact of the complex array of fungal activities in the soil.

Mycorrhizae[12]

One of the most ecologically and economically important activities of soil fungi is the mutually beneficial association (**symbiosis**) between certain fungi and the roots of higher plants. This association is called **mycorrhizae**, a term meaning "fungus root." Mycorrhizae are the rule, not the exception, for most plant species, including the majority of economically important plants. In natural ecosystems most plants are quite dependent on mycorrhizal relationships and cannot survive without them. Mycorrhizal structures have been found in fossils of plants that lived some 400 million years ago, indicating that mycorrhizal infection may have played a role in the evolutionary adaptation of plants to the land environment. Research shows that plants open themselves most readily and send the most sugars to those mycorrhizal fungi that are best at supplying them with soil nutrients. For their part, the fungi will direct the most nutrients to the roots that offer the best supply of sugars. Working much like a buyers and sellers in a classical human free market, these plant and fungus behaviors promote effective partnerships and guard against freeloading cheaters.

Benefits to Each Partner. Mycorrhizal fungi derive an enormous survival advantage from teaming up with plants. Instead of having to compete with all the other soil heterotrophs for

[12]For a comprehensive, well-written, and authoritative book on all aspects of mycorrhizal associations, see Smith and Read (2008). For meta-analysis of research on the efficacy of inoculation with mycorrhizal fungi in restoration ecology, see Hoeksema et al. (2010). The research on the plant-fungus "market place" see Kiers et al. (2011). For a brief overview of current thinking about mycorrhizal associations and their ecological implications, see Forsberg et al. (2012).

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decaying organic matter, the mycorrhizal fungi obtain sugars directly from the plant's root cells. This represents an energy cost to the plant, which may devote as much as 5–30% of its total photosynthate production to its mycorrhizal fungal symbiont.

In return, plants receive some extremely valuable benefits from the fungi. The fungal hyphae grow out into the soil many centimeters from the infected root, reaching farther and into smaller pores than could the plant's own root hairs. This extension of the plant root system increases its efficiency, providing perhaps ten times as much absorptive surface as the root system of an uninfected plant.

The most frequently reported benefit to plants from the mycorrhizal association is the greatly enhanced ability of plants to take up phosphorus from low-phosphorus soils. The fungi also assist with plant acquisition of other nutrients that are relatively immobile and present in low concentrations in the soil solution. Water uptake may also be improved by mycorrhizae, making plants more resistant to drought and salinity stress (Table 11.6). In extremely acid soils, this fungal relationship protects plants from aluminum toxicity (see Section 9.7), while in soils contaminated with high levels of metals, mycorrhizae protect the plants from excessive uptake of these potential toxins (see Section 18.7). There is evidence that mycorrhizae also protect plants from certain soil-borne diseases and parasitic nematodes by producing antibiotics, altering the root epidermis, and competing with fungal pathogens for infection sites. For all these reasons, the use of mycorrhizae can be a powerful tool in land restoration projects as well as in some agricultural situations.

Ectomycorrhiza. Two types of mycorrhizal associations are of considerable practical importance: **ectomycorrhiza** and **endomycorrhiza**. The ectomycorrhiza group includes hundreds of different fungal species associated primarily with temperate- or semiarid-region trees and shrubs, such as pine, birch, hemlock, beech, oak, spruce, and fir. These fungi, stimulated by root exudates, cover the surface of feeder roots with a fungal mantle. Their hyphae penetrate the roots and develop in the free space around the cells of the cortex but do not penetrate the cortex cell walls (hence the term *ecto*, meaning outside). Ectomycorrhizae cause the infected root system to consist primarily of stubby, white structures with a characteristic Y shape (Figure 11.33*a*,*b*). These Y-shaped structures provide evidence of mycorrhizal infection that is visible to the naked eye if one carefully excavates the roots.

Endomycorrhiza. The most important members of the endomycorrhiza group are called **arbuscular mycorrhizae** (AM). When forming AM, fungal hyphae actually penetrate the cortical root cell walls and, once inside the plant cell, form small, highly branched structures known as **arbuscules** (Figure 11.33*d*). These structures serve to transfer mineral nu-

Table 11.6
Effect of Arbuscular Mycorrhizae (AM) on Tomato Root Colonization, Fruit Yield, and Nutrient Uptake with Nonsaline or Saline Water
Very small amounts of inoculum were added to the potting mix in seedling trays. Mycorrhizal inoculation increased all parameters, but the greatest benefits of AM accrued under saline conditions. AM-inoculated plants under saline conditions yielded 5.3 kg fruit/m^2, not statistically different from the 5.8 kg fruit/m^2 yield of noninoculated plants under nonsaline conditions.

Irrigation water treatment	AM root colonization	Fruit yield	Nutrient content of plant shoot					
	Percent increase resulting from inoculation with AM fungi							
			P	K	Na	Cu	Fe	Zn
Nonsaline (EC_w = 0.5 dS/m)	166	29	44	33	21	93	33	51
Saline (EC_w = 2.4 dS/m)	293	60	192	138	7	193	165	120

Data selected from Al-Karaki (2006).

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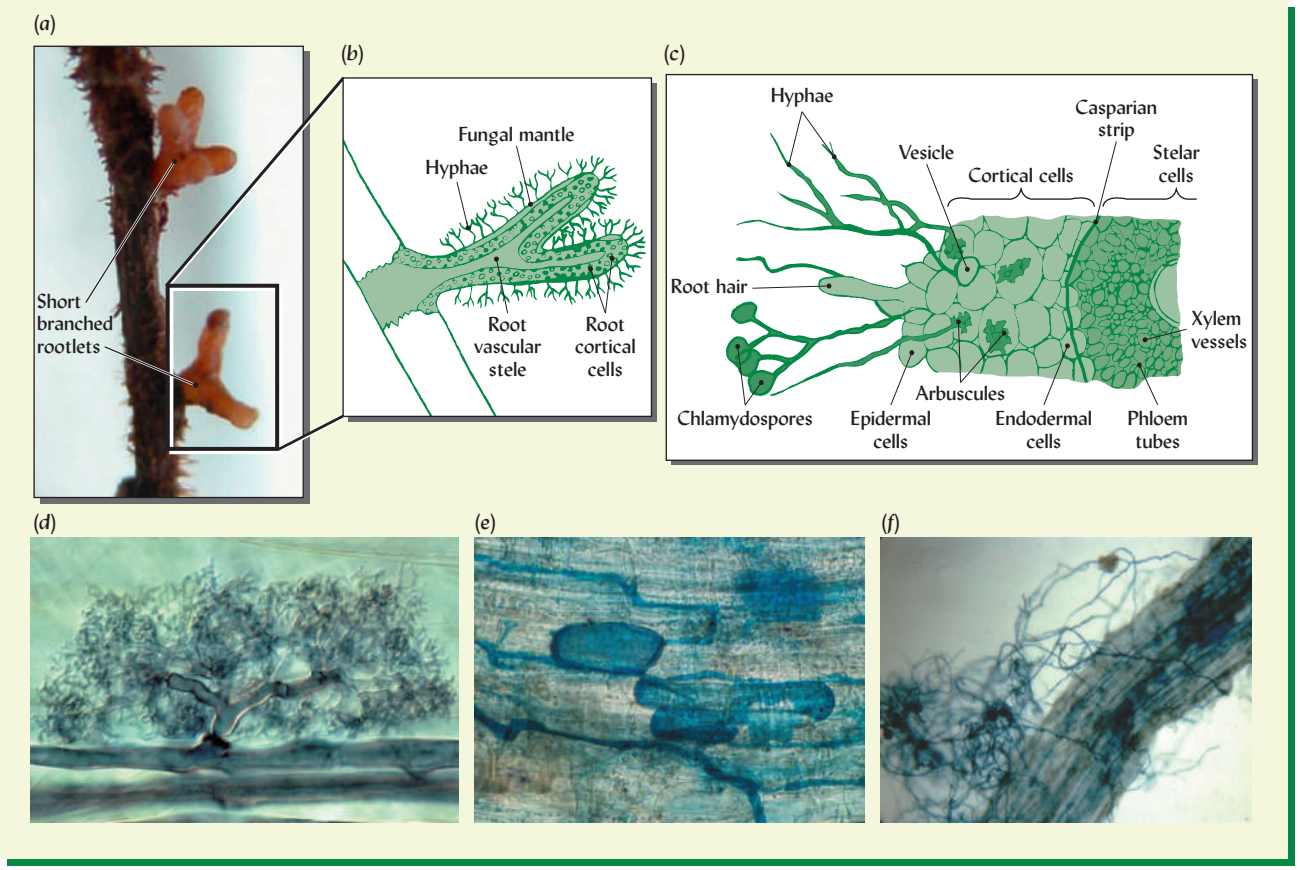

Figure 11.33 *Diagram of ectomycorrhiza and arbuscular mycorrhiza (AM) associations with plant roots. (a) The ectomycorrhiza association produces short branched rootlets that are covered with a fungal mantle. (b) Fungal hyphae grow between the root cells, forming the Hartig net, but do not penetrate the cells. The hyphae also extend far out into the soil. (c) In contrast, the AM fungi penetrate not only between cells but into certain root cortical cells as well. Within these cells, the fungi form arbuscules (d), structures that transfer nutrients between the plant and the fungus. Many AM fungi also form vesicles (e), structures in which the fungi stores its cache of sugars from the plant. The symbiotic fungi form extensive networks of hyphae that act to greatly extend the reach of the plant root system (f). In both types of association, the host plant provides sugars and other food for the fungi and receives in return essential mineral nutrients that the fungi absorb from the soil.* (Diagrams courtesy of Ray R. Weil; photos courtesy of (*a*) Ray R. Weil, (*d*) Mark Brundrett, (*e*) Courtesy of Charles White (*f*) R. P. Schreiner, USDA-ARS)

trients from the fungus to the host plants and sugars from the plant to the fungus. Other structures, called **vesicles**, are usually also formed and serve as storage organs for the mycorrhizae (Figure 11.33*e*).

Nearly 100 identified species of fungi form these endomycorrhizal associations in soils from the tropics to the arctic. Most native plants and agricultural crops can form AM associations and do not grow well on unfertilized soil in their absence. Many plants in the Legume family are especially dependent on mycorrhizae, not only to obtain sufficient phosphorus, but also to enhance their nitrogen-fixing symbiosis with rhizobia bacteria (Section 13.10). AM fungi are agriculturally most important where soils are low in nutrients, especially phosphorus (Figure 11.34). Two economically important groups of plants that do *not* form mycorrhizae are the *Cruciferae* (mustards, cabbage, radish, rapeseed) and the *Chenopodiaceae* (beet and spinach).

Research on AM continues to reveal the ecological and practical significance of this symbiosis. The importance of mycorrhizal hyphae in stabilizing soil aggregate structure is becoming increasingly clear (see Box 4.4). Also, AM fungi have been observed to form hyphal interconnections among nearby plants in forest, grassland, and pasture ecosystems. These hyphal connections can transfer nutrients from one plant to another, sometimes resulting in a complex, four-way symbiotic relationship (Figure 11.35). The ecological significance of these AM-mediated nutrient transfers is not yet well understood.

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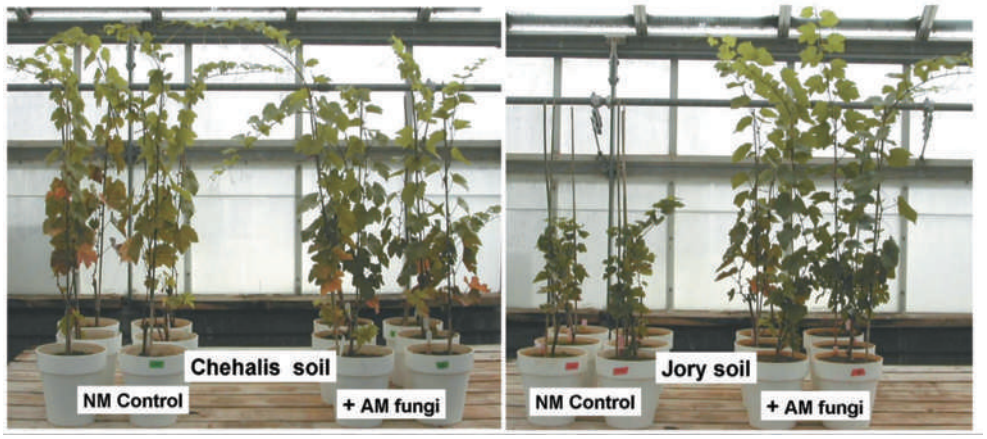

Figure 11.34 *The efficacy of inoculating with mycorrhizal fungi (+ AM fungi) largely depends on the phosphorus status of the original soil before any mycorrhiza are added (NM Control). (Right) Here, grape vines growing in Jory soil (an Ultisol with low P availability) show a dramatic growth response to the addition of the mycorrhizal inoculum. (Left) The same variety of grape vine is unaffected when growing in the Chehalis soil, which is a Mollisol with a high level of P fertility.* (R. P. Schreiner, USDA-ARS)

Managing Mycorrhizae. Because of the near ubiquitous distribution of native mycorrhizal fungi, adding mycorrhizal inoculum rarely makes a difference in normal, biologically active soils. However, there are steps that can ensure good mycorrhizal colonization. Soil tillage destroys hyphal networks; therefore physical soil disruption is likely to decrease the effectiveness of native mycorrhizae. It is also best to avoid too-frequent use of nonhost species, long periods of soil bareness, or heavy fertilization with phosphorus. In addition, the buildup of effective mycorrhizae in soils is favored by growing a diversity of host plant species as continuously as possible. The importance of maintaining host plants is exemplified by the case of Douglas fir forest regrowth. Clear-cutting of Douglas fir stands is commonly followed by suppression of hardwood trees, which are viewed as weed species that compete with the regenerated Douglas fir trees. However, it has been found that the young Douglas firs survive and grow much better if some hardwood saplings are allowed to remain to provide host continuity and serve as an inoculum source for AM fungi.

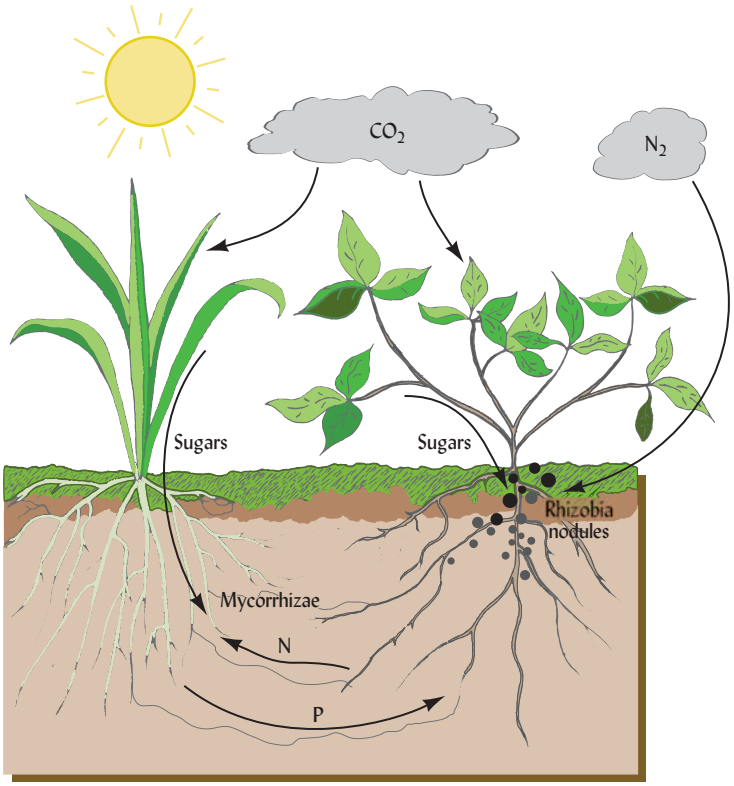

Figure 11.35 *Mycorrhizal fungi, rhizobia bacteria, legumes, and nonlegume plants can all interact in a four-way, mutually beneficial relationship. Both the fungi and the bacteria obtain their energy from sugars supplied through photosynthesis by the plants. The rhizobia form nodules on the legume roots and enzymatically capture atmospheric nitrogen, providing the legume with nitrogen to make amino acids and proteins. The mycorrhizal fungi infect both types of plants and form hyphal interconnections between them. The mycorrhizae then not only assist in the uptake of phosphorus from the soil, but can also directly transfer nutrients from one plant to the other. Isotope tracer studies have shown that, by this mechanism, nitrogen is transferred from the nitrogen-fixing legume to the nonlegume (e.g., grass) plant, and phosphorus is mostly transferred to the legume from the nonlegume. The nonlegume grass plant has a fibrous root system and an extensive mycorrhizal network, which is relatively more efficient in extracting P from soils than the root system of the legume. Research indicates that some direct transfer of nutrients via mycorrhizal connections occurs in many mixed plant communities, such as in forest understories, grass–legume pastures, and mixed cropping systems.* (Diagram courtesy of Ray R. Weil)

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Applying Mycorrhizal Inoculum. There may be a need to inoculate soils with mycorrhizal fungi where native populations are very low or conditions for infection are unusually adverse. Examples include soils that have been subjected to broad spectrum fumigation; extreme soil heating, drying, or salinization; drastic disturbance such that subsoil layers are brought to the surface; or long periods without vegetative cover (such as surface soil stockpiled during mining or construction activities as shown in Figure 1.19). Successful restoration of healthy vegetation to such denuded soils often requires inoculation with effective mycorrhizal fungi.

Commercial Inoculants. Many ectomycorrhizal fungi are facultative symbionts (they can also live independently in the soil) and therefore can be cultured in large quantities on artificial media. Effective and pathogen-free ectomycorrhizae inoculants can, therefore, be easily produced for use on such trees as conifers, oaks, hickory, birch, willow, poplar, pecan, and eucalyptus. Commercial ectomycorrhizal inoculants for use in planting such trees in warm climates usually contain the fungus *Pisolithus tinctorius*, while those used to inoculate soils in cold climates typically contain *Rhizopogon* species. On infertile soils, use of these ectomycorrhizal inoculants is likely to increase tree survival and growth by 50–500%.

Inoculation with AM fungi may be more difficult, although sometimes soil from a mature ecosystem containing the desired plant species can be brought in as inoculum to supply the necessary mycorrhizal fungi. Although AM fungi cannot be grown in pure culture, concentrated, disease-free inoculants can be made using specially prepared roots from an appropriate well-colonized host plant. Again, little response to inoculation is likely on healthy, biologically active soils, but dramatically positive effects are often obtained with such inoculum on highly disturbed or infertile sites.

11.10 SOIL PROKARYOTES: BACTERIA AND ARCHAEA

The organisms described in the previous sections—from mammals to molds—all belong to the Eukarya domain. The organisms in the other two domains of life, the Bacteria and the Archaea, are prokaryotes—their cells lack a nucleus surrounded by a membrane. However, despite their similar appearance under the microscope, archaea are evolutionarily quite distinct from bacteria. For example, Archaea cell membranes exhibit major chemical differences from bacterial membranes, such as the use of isoprene derivatives instead of fatty acids in their construction. In some respects, genetic analysis suggests that Archaea may be as closely related to plants or people as they are to bacteria! Until recently, the archaea were thought of as rare and primitive creatures that live in only the most extreme and unusual environments on Earth—salt-saturated waters (see Figure 11.36), extremely acid or alkaline soils, deeply frozen ice, boiling hot water, anaerobic sediments, and the like. However, molecular techniques now suggest that archaea are also common in more "normal" environments and probably represent about 10% of the microbial biomass in typical upland soils. We will consider the archaea together with the bacteria in this section, calling them prokaryotes when the discussion applies to members of both domains.

Another recent insight provided by molecular identification techniques is that although we previously had no idea how little we knew, now we do! Traditionally, scientists enumerated and identified soil microbes by culturing them in petri dishes on agar of various kinds. We now know that the thousands of species so identified represent less than 0.1% of the species present in soils—most prokaryotes simply cannot be cultured on lab media. While the usual concept of a "species" is difficult to apply to single-celled microorganisms that reproduce asexually, "kinds" of organisms are now estimated by "genome equivalents" of DNA information. Molecular techniques that use the DNA, RNA, and fatty acids from soils to "fingerprint" the microbial community have truly thrown open new frontiers for soil microbiology (see Box 11.2).

Characteristics

Prokaryotes range in size from 0.5 to 5 μm, considerably smaller in diameter than most fungal hyphae (Figure 11.38). The smaller ones approach the size of the average clay particle

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Figure 11.36 *Seawater evaporation lagoons constructed to collect sea salt have been turned red in color by blooms of halobacterium, an Archaea with a red photosynthesizing pigment.* (Photo courtesy of Ray R. Weil)

(see Figure 11.1). Prokaryotes are found in various shapes: nearly round (coccus), rodlike (bacillus), or spiral (spirillum). In the soil, the rod-shaped prokaryotes seem to predominate. Many prokaryotes are motile, swimming about in the soil water films by means of hair-like cilia or whip-like flagella. Others heavily colonize the nutrient-rich surface of plant roots (Figure 11.39). In many situations prokaryotes act as social creatures in that large numbers of individual cells act together in a coordinated manner to form what some have called a "superorganism," somewhat analogous to the ant colonies or slime molds slugs discussed in Sections 11.5 and 11.6. This collective action is made possible by communication via both exocellular chemical signals that diffuse through the soil solution and apparently also by proteins shared among cells via intercellular connections. As one result, bacterial cells often form biofilms—dense colonies with cells embedded in layers of excreted polysaccharides. Such biofilms may alter the soil environment by clogging pores, and covering mineral and root surfaces.

Prokaryote Diversity in Soils

The numbers of prokaryotes in soils are enormous but extremely variable, ranging from a few billion to more than a trillion in each gram of soil. A biomass of 400–5000 kg/ha live weight is commonly found in the upper 15 cm of fertile soils (see Table 11.4).

Their small size and ability to form extremely resistant resting stages that survive dispersal by winds, sediments, ocean currents, and animal digestive tracts have allowed prokaryotes to spread to almost all soil environments. The prokaryote diversity in a handful of soil is said to be comparable to the diversity of insects, birds, and mammals in the Amazon Basin! Their extremely rapid reproduction (generation times of a few hours in the lab to a few days in favorable soil) enables prokaryotes to increase their populations quickly in response to favorable changes in soil environment and food availability. Early soil microbiologist Martinus Beijerinck is well known for concluding about soil microorganisms that "everything is everywhere and the milieu selects." That is, the microbial community reflects the soil environment rather than geography. For example, the prokaryote community in a well-drained soil under grassland vegetation with a neutral pH is likely to be quite similar to a well-drained neutral soil under grassland on another continent, but quite different from the community in a geographically nearby soil that is very acid or poorly drained. By the same token, if a new substrate is added—even an industrial waste—populations of prokaryotes capable of feeding on it will likely soon emerge. On the other hand, recent research has questioned the relative lack of geographic differentiation in soil microbial communities.

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BOX 11.2

SOIL MICROBIOLOGY IN THE MOLECULAR AGE

GUEST COMMENTARY BY STEPHANIE YARWOOD[a]

The study of soil microorganisms has dramatically changed in recent decades. From the 1850s to the early 1990s, scientists studied soil microbes by isolating them from soil, growing them on various media in the lab and studying them in pure culture. This approach yielded many important insights. For example, in 1887 Sergei Winogradsky described the metabolic strategies of chemolithotrophy (autotrophic feeding on minerals) and in 1900 Martinus Beijerinck isolated nitrogen-fixing bacteria from legume root nodules. Early on, soil microbiologists noted that when bacteria from a soil sample were enumerated by direct count under a microscope, the numbers were 100s–1000s of times higher compared to when bacteria from the same sample were enumerated by growing on media in a petri dish.

Resolving this "great plate count anomaly" required a new approach that did not rely on microscopes or petri dishes. Technologies were developed focusing on molecular components of the cell: DNA, RNA, lipid, and protein. The most used today is DNA. Vigdis Torsvik was the first to successfully extract DNA directly from soil. By the early 1990s soil microbiologists were using extracted DNA in a variety of molecular-based approaches. Using DNA as the marker for soil microorganisms revealed that each gram of soil may contain 10^9 individual bacterial cells and, although the number is still debated, that same gram of soil may contain about 4000 species. These methods also lead to the discovery of entire groups of microbes never before cultured or described, including a new phylum

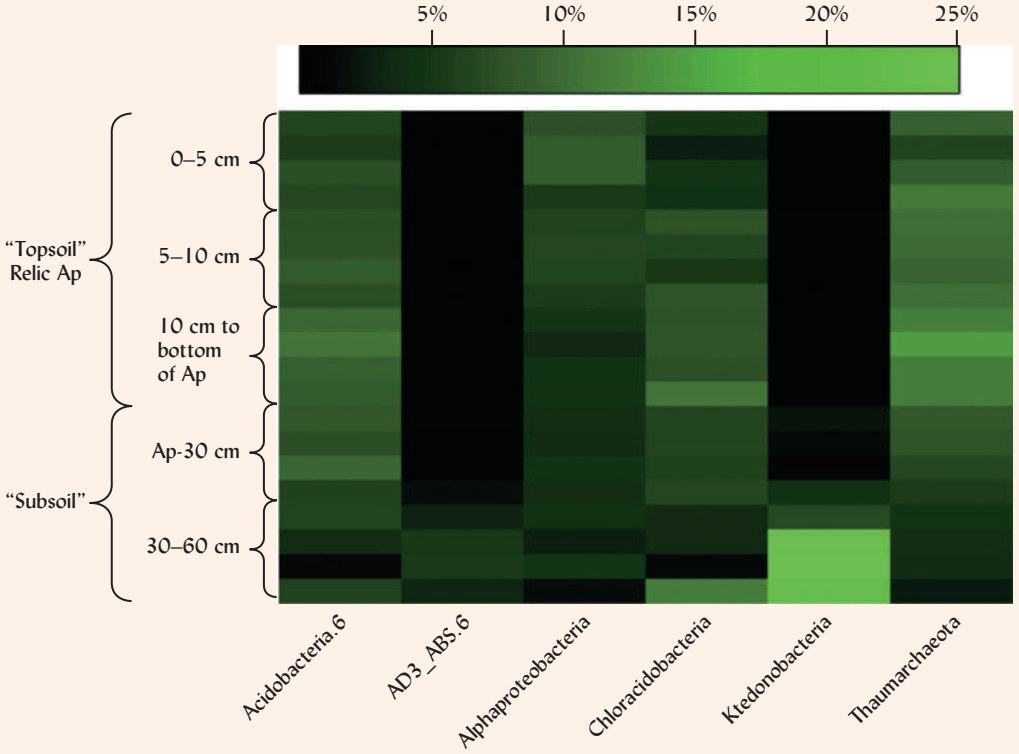

Figure 11.37 *A "heatmap" diagram showing the relative abundance of DNA sequences matching known bacterial and archaeal classes at various soil depths in a cultivated Ultisol in Beltsville in Maryland, USA. Grain and forage crops were produced in these fields for nearly 200 years (the last 11 under no-till management) prior to sampling for this study. Each row of cells represents a soil sample from one depth interval in one plot. The brackets indicate the five depth classes, each with samples from four replicate plots. A columns represents one of the six classes of microbes found. The colors indicate the relative abundances of each class at each depth, ranging from 0.01 (black) to 25.0% (bright green) of the total sequences extracted in that sample. The data show that Alphaproteobacteria were most abundant at the surface, Thaumarchaeota and Acidobacteria (class 6) were most abundant at the Ap horizon boundary, and Ktedonobacteria and phylum AD3, class ABS.6 were most abundant from 30 to 60 cm. AD3 is a "candidate" phylum without a formal name, as none of its members have yet been cultured. The lower boundary of the plowed layer (Ap horizon) generally occurred between 15 and 25 cm below the soil surface.* (Diagram courtesy of G. Dlott and S. Yarwood, University of Maryland)

(continued)

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BOX 11.2

SOIL MICROBIOLOGY IN THE MOLECULAR AGE *(CONTINUED)*

called Acidobacteria that may represent 25% of all the bacteria in some soil types. In fact, scientists now believe that the nine genera of bacteria (Agrobacterium, Bacillus, Pseudomonas, Streptomyces, etc.) considered in the late 1970s to be of significance in soils, actually account for only 5% of the of soil bacteria.

Studies of soil DNA were initially focused on genes like the bacterial 16S rRNA that contains the genetic information needed to make cell ribosomes. The 16S is a good target to examine bacterial diversity because every living cell needs ribosomes in order to make protein. The code for this gene (the sequence of the bases A, C, T, G) is different in each species, allowing microbiologists to identify which microbes are present. For example, the 16S rRNA gene was used to characterize bacteria and archaea above and below the plow layer (Ap) in an Ultisol managed under no till farming for nearly 20 years (Figure 11.37). The seven most abundant classes of organisms are shown. From this diagram it is clear microbial communities change with depth, with some organisms more abundant at the surface, but the abundance of others increasing with depth.

Unfortunately, because every microbe has the 16S rRNA gene, this method does not reveal the *function* of the organisms within the soil profile. The next step, therefore, has been to target functional genes. The gene coding for nitrous oxide reductase, for example, can be used to characterize denitrifying bacteria (see Section 13.9). Functional genes can be quantified to determine the population size, and DNA sequencing allows identification of the organisms involved.

Today, with the decreased cost of DNA sequencing and the increased power of computers, soil microbiologists can identify or sequence the entire complement of genes—the genome—in a given organism. In fact, they are now sequencing *all* the sets of genes for *all* the organisms in a whole microbial community—the metagenome. Metagenomics refers to the collection and analysis of all the genetic information in a community's metagenome (such as all the genes in a complex soil sample). The goals of this approach are to understand what individual species are capable of doing and what conditions favor their growth.

These new molecular methods also help microbiologists create improved approaches to culturing microbes in the lab. Although less than 1–2% of soil bacterial species are in culture today, soil microbiologists have had recent success in culturing difficult-to-grow microbes, including *Acidobacteria*. Culturing remains a valuable approach, because it helps confirm functions and life strategies predicted by the DNA sequencing data. The combination of culturing and molecular methods is revealing an increasingly detailed view of the most diverse microbial community on Earth. With the advent and rapid expansion of molecular methods, soil microbiologists are working toward a day when knowledge of which soil microbes are present in a particular soil will help us predict how that soil will function.

[a]Dr. Yarwood is a soil microbial ecologist at the University of Maryland.
For a review of advances in molecular soil microbiology see Zhu et al. (2013). The first isolation of bacterial DNA from soil was reported in the classic paper, by Torsvik (1980).

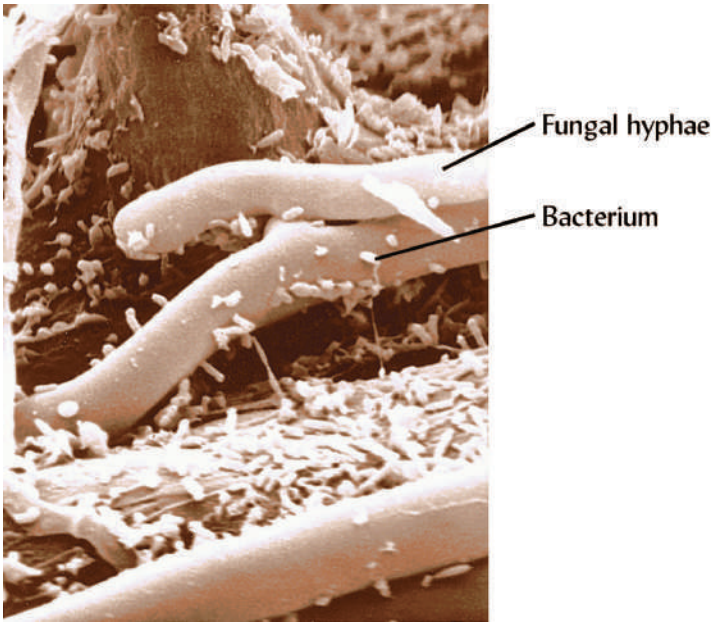

Figure 11.38 *Fungal hyphae associated with much smaller rod-shaped bacteria.* (Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society)

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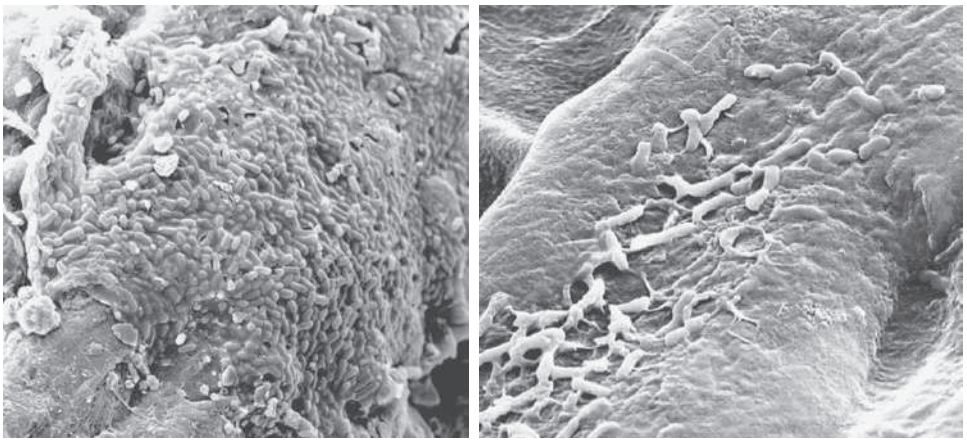

Figure 11.39 *Bacteria colonies on the surface of a wheat root (left) and a corn root (right). The bacteria on the wheat root are embedded in their own secreted mucilage. The rhizosphere soil and the root surface itself are usually crowded with bacteria that are integral to the plant–soil–microbe system.* (Cryo scanning electron micrographs courtesy of Margaret McCully, CSIRO Plant Industry, Canberra, Australia)

Sources of Energy

Soil prokaryotes are either autotrophic or heterotrophic (see Section 11.2). The autotrophs obtain their energy from sunlight (photoautotrophs) or from the oxidation of inorganic constituents such as ammonium, sulfur, and iron (chemoautotrophs) and obtain their carbon from carbon dioxide or dissolved carbonates. Autotrophic bacteria are not as diverse as heterotrophs in soils, but they play vital roles in controlling nutrient availability to higher plants and other organisms.

Most soil bacteria are heterotrophic—both their energy and their carbon come from organic matter. Heterotrophic bacteria, along with fungi, account for the general breakdown of organic matter in soil. The bacteria often predominate on easily decomposed substrates, such as animal wastes, starches, and proteins. Where oxygen supplies are depleted, as in wetlands, nearly all decomposition is mediated by prokaryotes and Archaea play a relatively large role. Certain gaseous products of anaerobic metabolism, such as methane and nitrous oxide, have major effects on the global environment (see Sections 12.9 and 13.9).

Importance of Prokaryotes

Prokaryotes participate vigorously in virtually all of the organic transactions that characterize a healthy soil. Prokaryotes hold near monopolies in the oxidation or reduction of certain chemical elements in soils (see Sections 7.4 and 7.6).

Some autotrophic prokaryotes obtain their energy from such inorganic oxidations, while anaerobic and facultative bacteria reduce a number of substances other than oxygen gas. Many of these biochemical oxidation and reduction reactions have significant implications for environmental quality as well as for plant nutrition. For example, through nitrogen oxidation (nitrification), selected bacteria oxidize relatively stable ammonium nitrogen to the much more mobile nitrate form of nitrogen.

Scientists are working to harness, even improve, the prokaryotes' broad range of enzymatic capabilities to help with the remediation of soils polluted by crude oil, pesticides, and various other organic toxins (see Section 18.6). The Archaea are the most important group in the breakdown of hydrocarbon compounds, such as petroleum products. Likewise, certain archaeans oxidize sulfur, yielding plant-available sulfate ions, but also potentially damaging sulfuric acid (see Sections 9.6 and 13.20).

Prokaryote oxidation and reduction of inorganic ions such as iron and manganese not only influence the availability of these elements to other organisms (see Section 15.5), but also help determine soil colors (see Section 4.1). A critical process in which bacteria are prominent is nitrogen fixation—the biochemical combining of atmospheric nitrogen with hydrogen to form organic nitrogen compounds usable by plants (see Section 13.10).

Cyanobacteria

Previously classified as blue-green algae, **cyanobacteria** contain chlorophyll, which allows them to photosynthesize like plants. Cyanobacteria are especially numerous in rice paddies

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and other wetland soils and fix appreciable amounts of atmospheric nitrogen when such lands are flooded (see Section 13.12). These organisms also exhibit considerable tolerance to saline and arid environments and are important in forming microbiotic crusts on desert soils (Section 11.14). Research suggests that the metabolism of certain photosynthetically efficient cyanobacteria may be manipulated to produce biofuels such as 2,3-butanediol.

Soil Actinomycetes

Actinomycetes is the term traditionally used for bacteria in the order *Actinomycetales* within the phylum **Actinobacteria**. Filamentous and often profusely branched (see Figure 11.40), they may appear somewhat like tiny fungi, but their genetic makeup and cellular properties clearly place them in the Bacteria domain—they have no nuclear membrane, are about the same diameter as other bacteria, and often break up into spores that closely resemble cocci bacterial cells. Because of their unique appearance and metabolic capabilities, actinomycetes have received much attention from soil microbiologists. Actinomycetes are often among the most abundant of the prokaryote groups (see Table 11.4), and their biomass often exceeds that of the other bacteria. Where the acidity is not too great, actinomycetes are especially numerous in soils high in organic matter, such as old meadows or pastures.

Decomposition Activities. Generally aerobic heterotrophs, the actinomycetes live on decaying organic matter in the soil or on compounds supplied by plants with which certain species form parasitic or symbiotic relationships. Actinomycetes undoubtedly are of great importance in the decomposition of soil organic matter and the liberation of its nutrients. They are capable of breaking even resistant compounds, such as cellulose, chitin, and phospholipids, into simpler forms. They often become dominant in the later stages of decay when the easily metabolized substrates have been used up. They are very important in the final (curing) stages of composting (see Section 12.10).

Special Attributes. The earthy aroma of organic-rich soils and freshly plowed land is credited mainly due to actinomycete-produced *geosmins*, volatile derivatives of terpene. Actinomycetes develop best in moist, warm, well-aerated soil. However, they tolerate low osmotic potential and are active in arid-region, salt-affected soils, and during periods of drought. They are generally rather sensitive to acid soil conditions, with optimum development occurring at pH values between 6.0 and 7.5. Some actinomycete species tolerate relatively high temperatures. In forest ecosystems, much of the nitrogen supply depends on actinomycetes that fix atmospheric nitrogen gas into ammonium nitrogen that is then available to plants (see Section 13.12). Many actinomycete species, especially in the genus *Streptomyces*, produce compounds that kill other microorganisms, and these "antibiotics" have become extremely important in human medicine (see Box 11.3).

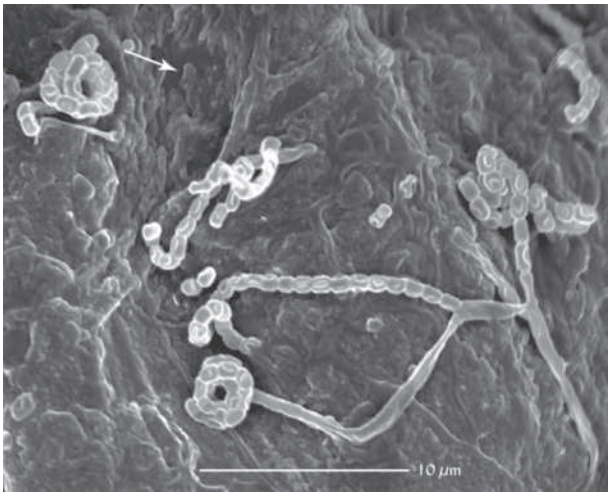

Figure 11.40 *Strands of an actinomycete, a type of filamentous bacteria, growing on the surface of a soil biopore (an old root channel). The filaments, some breaking into the beadlike spores by which this organism reproduces, are about 0.8 μm in diameter. Some of the actinomycete filaments are embedded in mucilage of the soil pore (e.g., at arrow). The image is from 1.5 m deep in a clayey soil (poorly structured Alfisols) of a wheat field in eastern New South Wales, Australia. The biopore surfaces are generally smooth, coated with illuvial clay and residues of old alfalfa roots. Although fungi commonly occupy old root channels, few were found in this soil, perhaps because of the antibiotic and chitinase secretions of the actinomycetes.* (Cryo-SEM image courtesy of Margaret McCully, CSIRO Plant Industry, Canberra, Australia)

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BOX 11.3

A POST-ANTIBIOTIC AGE ON THE HORIZON?[a]

Antimicrobial compounds—commonly called antibiotics—inhibit or kill specific microorganisms. Most antibiotics kill by interfering with a few physiological reactions specific to bacteria, for instance, the generation of bacterial cell walls; therefore they are not toxic to unrelated organisms, such as humans and other animals. Certain soil bacteria and fungi have evolved the capability of producing these compounds as part of their struggle for survival in the soil. Being bathed in their own chemical warfare agents, most of these spore-forming microbes have also evolved immunities to many types of antibiotics. With the mid-20th-century advent of antibiotic "miracle drugs," these same compounds enabled humans to all but conquer infectious bacterial diseases, which up until that time were the most common cause of human deaths. Penicillin, the first antibiotic drug, was derived from a soil fungus (*Penicillium* spp.) that contaminated some laboratory petri dishes in 1928. In 1943, streptomycin was discovered, leading to the first of many antibiotic drugs synthesized by soil bacteria belonging to the genus *Streptomyces*. Likely you are alive today because an antibiotic produced by a soil organism (e.g., chloramphenicol, erythromycin, tetracycline, and vancomycin) was available to save your life when you came down with a bacterial infection (e.g., pneumonia or a dirty wound).

Unfortunately, the efficacy of these drugs is being rapidly eroded by the increase in resistant strains of pathogenic bacteria. Nearly seven times as many people die from infection acquired in hospitals today as compared to 20 years ago and most of the bacteria causing these illnesses show resistance to at least one antibiotic. The potentially fatal human pathogens Enterococci and Staphylococci have now developed resistance to virtually every antibiotic drug available in the medical arsenal. What is causing the alarming rise in resistance that threatens to return humankind to the pre-antibiotic era?

Overexposure to antibiotic drugs has exerted tremendous selection pressure for resistance in the pathogen populations. Antibiotic now permeate the environment—some 18 million kg are used annually in the United States alone. Part of the problem stems from overuse and misuse of human drugs by doctors, patients (did you take *all* the pills prescribed—or did you stop when you felt better, letting the most resistant bacteria live on?), hospitals, and consumers (does bath soap really need to contain an antibiotic when the soap itself kills bacteria by lysing their cell walls?). Worryingly, the resistant bacteria may spread in the environment; antibiotic-resistant bacteria have been found in rivers near sewage outfalls.

But the principal source of antibiotics in the environment is the enormous amount used for nonmedical purposes. In fact, in the United States, some 87% of the antimicrobial drugs produced (nearly 15 million kg/y) is devoted to nonhuman uses, most of this as a growth-promoting feed additive for healthy (not sick) poultry, hog, and cattle in industrial-style farms. Such subtherapeutic feed additive use of antibiotics is several times greater in China, the world's biggest antibiotics producer. Much of the antibiotic ingested by the livestock passes through the digestive tract unchanged and accumulates in the manure that is eventually spread on farm fields. Once in the soil, the compounds are known to retain their antibiotic activity even if adsorbed for long periods to clay surfaces (see Figure 8.38). Crops (corn, onion, and cabbage) growing on soils fertilized with such manure can take up small amounts of the antibiotic, presenting the possibility that the antibiotics added to livestock feed may end up causing human allergic reactions and selecting for resistance in the human digestive tract. Scientists using molecular techniques have shown that soils provide a large reservoir and breeding ground for antibiotic resistance. Common soil decomposer bacteria (Figure 11.41) are increasingly developing genes for resistance that they readily pass on to other completely unrelated bacteria—such as human pathogens.

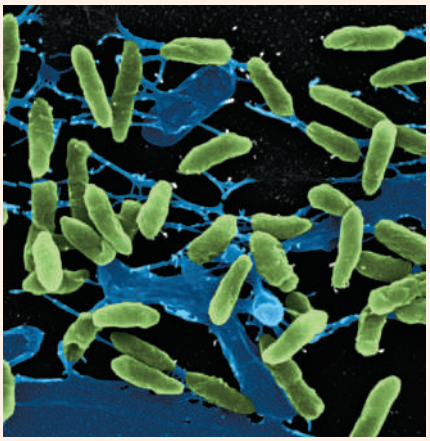

Figure 11.41 *Scanning electron micrograph showing a colony of the common soil bacteria, Pseudomonas, found to harbor genes for antibiotic resistance and transfer them to human pathogen bacteria.* (Gautam Dantas and Kevin Forsberg)

The large and continuous antibiotic presence in industrial animal facilities and in manured soils almost certainly hastens the evolution of antibiotic resistance in bacteria, including in human pathogens. While the problem has been known by scientists since the 1980s, policymakers in industrialized countries have been slow to realize the need to eliminate such careless use of these life-saving substances. Recent discovery in a soil from Maine of a new class of antibiotics that seems less likely to engender resistance should not lull society into inaction!

[a]For more on this topic, see Mellon et al. (2001), Kumar et al. (2005), D'Costa et al. (2006), Chander et al. (2007), and Zhu et al. (2013); on transfer of antibiotic resistance from soil microbes to human pathogens, see Pehrsson et al. (2013); on discovery of a new soil produced antibiotic named Teixobactin, which inhibits bacterial cell wall synthesis, see Ling et al. (2015).

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11.11 CONDITIONS AFFECTING THE GROWTH AND ACTIVITY OF SOIL MICROORGANISMS

Organic Resources

The addition of almost any energy-rich organic substance, including the compounds excreted by plant roots, stimulates microbial growth and activity. Generalist bacteria tend to respond most rapidly to additions of simple compounds such as starch and sugars, while fungi and actinomycetes overshadow the other microbes if added organic materials are rich in cellulose and other resistant compounds. In addition, if organic materials are left on the soil surface (as in forest litter), fungi dominate the microbial activity (Figure 11.29). Bacteria commonly play a larger role if the substrates are mixed into the soil, as by earthworms, root distribution, or tillage.

In addition, many bacteria adapted to life in the plant rhizosphere are sensitive to growth factors and signaling compounds released by plant roots. Many bacteria also communicate with organic compounds they produce to enable coordinated group action with other individuals of the same species or different species.

Oxygen Requirements

While most soil microorganisms are *aerobic* and use O_2 as the electron acceptor in their metabolism, some prokaryotes are *anaerobic* and use substances other than O_2 (e.g., NO_3^-, SO_4^-, or other electron acceptors). *Facultative* bacteria can use either aerobic or anaerobic forms of metabolism. All three of these types of metabolism are usually carried out simultaneously in different habitats within a soil. The zone of greatest microbial activity usually occurs just a few cm below the soil surface where oxygen is high and the soil is not too dry (Figure 11.42).

Moisture and Temperature

Optimum moisture potential for higher plants (−10 to −70 kPa) is also usually best for aerobic microbes. Too high a water content will limit the oxygen supply. Microbial activity is generally greatest when temperatures are 20–40 °C. The warmer end of this range tends to favor actinomycetes. Ordinary soil temperature extremes seldom kill bacteria and commonly only temporarily suppress their activity. However, except for certain **psychrophilic** species, most microorganisms cease metabolic activity below 3–5 °C, a temperature sometimes referred to as *biological zero* (see Section 7.8). Nonetheless, the concept of biological zero must be used with caution; bacterial and archeal activities have been documented at subzero temperatures in and under polar ice.

Figure 11.42 *A wood fence post pulled up after several years in the soil. Lines on the post indicate the soil surface when it was set in place. Decay of wood was greatest a few cm below the soil surface, where oxygen and moisture are in plentiful supply and create a zone of maximum biological activity. Keeping this phenomenon in mind (commonly referred to as the "fence post principle"), farmers often avoid deep incorporation of organic amendments.* (Photo courtesy of Ray R. Weil)

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Exchangeable Calcium and pH

Levels of exchangeable calcium and pH help determine which specific organisms thrive in a particular soil. Although some prokaryote species will thrive in any chemical condition found in soils, high calcium and near-neutral pH generally result in the largest, most diverse bacterial populations. Regardless of other soil properties, bacterial diversity has been found to increase dramatically with soil pH, from very acid soils to slightly alkaline ones (see Figure 9.25). In low pH, fungi become dominant. The effect of pH and calcium helps explain why fungi tend to dominate in forested soils, while bacterial biomass generally exceeds fungal biomass in most subhumid to semiarid prairie and rangeland soils.

11.12 BENEFICIAL EFFECTS OF SOIL ORGANISMS ON PLANT COMMUNITIES

The soil organism community is indispensable to plant productivity and the ecological functioning of soils. Of their many beneficial effects on plant communities, only the most important can be emphasized here.

Soil Organic Matter Formation and Nutrient Cycling

Perhaps the most significant biological function of soils is the decomposition of dead plant tissues. Soil organisms also assimilate wastes from animals (including human sewage) and other organic materials added to soils. As a by-product of their metabolism, microbes synthesize new compounds, some of which help to stabilize soil structure. When microbes die, their cell walls often bind to mineral particles forming an important part of soil humus. The bacteria, archaeans, and fungi assimilate some of the N, P, and S in the organic materials they digest. Excess amounts of these nutrients may be excreted into the soil solution in inorganic form either by the microbes themselves or by the nematodes and protozoa that feed on them. In this manner, the soil food web converts organically bound forms of N, P, and S into mineral forms that are taken up once again by higher plants.

Breakdown of Toxic Compounds

Many organic compounds toxic to plants or animals find their way into the soil. Some of these toxins are produced by soil organisms as metabolic byproducts, some are applied purposefully by humans as agri-chemicals to kill pests, and some are deposited in the soil because of unintentional environmental contamination. If these compounds accumulated unchanged, they would do enormous ecological damage. Fortunately, most biologically produced toxins do not remain long in the soil since soil ecosystems include organisms that not only are unharmed by these compounds but can use them as food.

Some toxins are **xenobiotic** (literally *strangers to life*) compounds foreign to biological systems, and these may resist attack by commonly occurring microbial enzymes. Soil prokaryotes and fungi are especially important in helping maintain a nontoxic soil environment by breaking down toxic compounds (see Section 18.6). Chemical weed killers or herbicides are examples of xenobiotic compounds that can have undesirable residual effects on future crops if they do not break down rapidly in the soil. Microbial breakdown of xenobiotics is usually fastest in the surface layers of soil, where microbial numbers are concentrated in response to the greater availability of organic matter and oxygen.

Inorganic Transformations

Nitrates, sulfates, and, to a lesser degree, phosphate ions are present in soils primarily due to inorganic transformations, such as the oxidation of sulfide to sulfate or ammonium to nitrate stimulated by microorganisms. Likewise, the availabilities of other essential elements, such as iron and manganese, are determined largely by microbial action. In well-drained soils, these elements are oxidized by autotrophic organisms to their higher valence states, in which forms they are quite insoluble. This keeps iron and manganese mostly in low solubility and nontoxic forms, even under fairly acid conditions (Section 15.7). If such oxidation did not occur, plant

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growth would be jeopardized because of toxic quantities of these elements in solution. Microbial oxidation also controls the potential for toxicity in soil contaminated with selenium or chromium (see Sections 15.9 and 13.8).

Nitrogen Fixation

Elemental nitrogen gas cannot be used directly by higher plants. The fixation of elemental nitrogen gas into compounds usable by plants is one of the most important microbial processes in soils (see Section 13.10). Actinomycetes in the genus *Frankia* fix major amounts of nitrogen in forest ecosystems; cyanobacteria are important in flooded rice paddies, wetlands, and deserts; and rhizobia bacteria are the most important group for the capture of gaseous nitrogen in grassland and agricultural soils. By far the greatest amount of nitrogen fixation by these organisms occurs in root nodules or in other associations with plants.

Rhizobacteria[13]

As pointed out in Section 11.7 and in Figure 11.25, the zone immediately around plant roots (the rhizosphere soil and the root surface itself, or **rhizoplane**) supports a dense population of microorganisms. Bacteria especially adapted to living in this zone are termed **rhizobacteria**, many of which are beneficial to higher plants (the so-called **plant growth–promoting rhizobacteria**). In nature, root surfaces are almost completely encrusted with bacterial cells, so little interaction between the soil and root can take place without some intervening microbial influence. In addition to those that ward off plant diseases (see Section 11.13), certain rhizobacteria promote plant growth in other ways, such as enhanced nutrient uptake or hormonal stimulation (for an example, see Table 11.7). Regarding hormonal effects, a single species of *Pseudomonas* bacteria has been shown to completely alter a plant's root growth, branching and root hair development in ways that benefit both the rhizosphere bacteria and its plant partner. The world of rhizobacteria is still largely uncharted, but advances in microbiological and chemical analysis tools are beginning to reveal an incredible level of complexity and interdependence. For example, more than 30,000 species (taxonomic units) of microbes and thousands of plant and microbial compounds have been documented within the rhizosphere of a sugarbeet plant. As fundamental knowledge increases, we can expect development of practical ways to take advantage of the many interactions to benefit higher plants.

Table 11.7
Rice Plants Respond to Inoculation with Growth-Promoting Rhizobacteria
Rice plants were grown in pots with clay soil that was puddled and flooded with water. All pots were fertilized with adequate N fertilizer, but only some were inoculated with various strains of rhizobia or bradyrhizobia bacteria. The bacteria colonized the rice rhizosphere (hence the term rhizobacteria) and changed the physiology of the rice plant, partly by producing the plant growth hormone IAA. Inoculated roots were more efficient at nutrient uptake. Analysis of N isotope tracers showed that the rhizobacteria did not cause significant amounts of N fixation.

		Uptake of nutrients by rice plants, mg/pot				
	Grain yield, g/pot	N	P	K	Fe	IAA[a] in the treatment rhizosphere, mg/L
Control—no inoculation	36.7	488	111	902	18.9	1.0
Inoculated with rhizobacteria	44.3	612	134	1020	23.6	2.1
Percent change	+21	+25	+21	+13	+25	+110

[a]Indol-3-acetic acid, a plant growth hormone.
Data calculated from Biswas et al. (2000).

[13]For an example of the complex and intimate relationship between one plant species and one of its rhizosphere bacteria, see Zamioudis et al. (2013).

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Plant Protection

Certain soil organisms attack higher plants, but others act to protect plant roots from invasion by soil parasites and pathogens. Plant diseases and the protective action of the soil microbes will be discussed in the next section.

11.13 SOIL ORGANISMS AND PLANT DAMAGE

Although most of the activities of soil organisms are vital to a healthy soil ecosystem and economic plant production, some soil organisms affect plants in detrimental ways that cannot be overlooked. For example, soil organisms successfully compete with plants for soluble nutrients (especially for nitrogen), as well as for oxygen in poorly aerated soils. Here we focus on the soil organisms that act as herbivores, parasites, or pathogens.

Plant Pests and Parasites

Soil Fauna. Many herbivorous soil fauna are injurious to the plants they feed on. Some rodents may severely damage young trees and farm crops. Snails and slugs in some climates are dreaded pests, especially of young leafy vegetables. Some ants are herbivorous (e.g., leaf-cutting ants), while others transfer aphids onto plants and so contribute to plant damage. Undoubtedly, the greatest damage to plants by soil fauna is caused by the feeding of nematodes and insect larvae. In nature, plants commonly sustain low levels of nematode and insect infestation, but under certain circumstances, infestation may be so great that the plant is killed or severely stunted. In agriculture, such infestations are often associated with lack of diversity that attends monocropping and insufficient organic matter addition. To prevent or diminish such infestations, large amounts of nematicide and insecticide chemicals are used in agriculture, often with unintended ecological results (see Section 11.14).

Microbes and Plant Disease. Disease infestations occur in great variety and are induced by many different microorganisms. Although bacterial blights and wilts are common, the fungi are responsible for the majority of soilborne plant diseases. Fungi of the genera *Pythium*, *Fusarium*, *Phytophthora*, and *Rhizoctonia* are especially prominent as soilborne agents of plant diseases described by such symptoms as *damping-off*, *root rots*, *leaf blights*, and *wilts*. Soils are easily infested with disease organisms, which are transferred from soil to soil by many means, including tillage or planting implements, transplant material, manure from animals that were fed infected plants, soil erosion, and wind-borne fungal spores and bacteria. Strict quarantine systems can restrict the transfer of soilborne pathogens from one area to another. Once a soil is infested, it is apt to remain so for a long time.

Deleterious Rhizobacteria. Some bacteria that live in the rhizosphere or on the rhizoplane inhibit root growth and function by various noninvasive chemical interactions. These nonparasitic **deleterious rhizobacteria** can cause stunting, wilting, foliar discoloration, nutrient deficiency, and even death of affected plants, but often the effects are subtle and difficult to detect. Their buildup may contribute to yield declines during long-term monoculture and aggravate problems in situations such as planting new trees in old orchards. On the other hand, by management that favors the deleterious rhizobacteria associated with certain weeds, scientists hope to be able to reduce weed seed germination and seedling growth and thereby reduce the use of herbicide (weed-killer) sprays on cropland and rangeland.

Plant Disease Control by Soil Management[14]

A detailed consideration of soil-related plant diseases is beyond the scope of this book text, but consideration of a few principles and examples of how soils may be managed to shift soil

[14]For a general overview of disease control by management of the soil ecosystem, see Stone et al. (2004); for a review of the scientific literature on disease and pest management using organic amendments, see Litterick and Harrier (2004). For an in-depth analysis of the influence on plant disease of soil factors affecting Mn and nitrate availability see Huber and Haneklaus (2007).

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microbial community composition and plant nutrition in favor of plant health. Taking pro-active steps to build a diverse, healthy soil–plant community is general preferable to reactively combating diseases once they become evident or preventative spraying. An integrated systems approach will ensure continuous vegetation by diverse plant species, as well as physical and chemical soil conditions that favor healthy plants and plant-beneficial microbial communities. Crop rotation can be very important in controlling a disease by growing nonsusceptible plants for several years between susceptible crops. A combination of organic matter (especially manure) addition, soil pH control (with sulfur) and rotation with nonsusceptible grasses has proved effective in preventing and suppressing the fungus *Phymatotrichopsis ominvorum*, which causes devastating root rots on some 2000 species of economically important plants (including trees, shrubs, forages, grains, and vegetables).

Tillage may help by burying plant residues on which fungal spores might overwinter. However, disease problems are often lessened in no-tillage systems in which the soil surface remains mulched with plant residues that maintain favorable soil temperature and moisture and a diverse soil community. Maintaining a surface mulch will also prevent the splashing of soil and fungal spores onto foliage by rain or irrigation water. Soil splash on an unmulched soil surface is a major cause of plant disease initiation and spread. Residues from certain green manure crops have been shown to chemically inhibit specific plant diseases. Direct management of soil physical and chemical properties can also be useful in disease control.

Soil PH. Regulation of soil pH is effective in controlling some diseases. For example, keeping the pH low (<5.2) can control both the actinomycete-caused *potato scab* and the fungal disease of turfgrass known as *spring dead spot.* Raising soil pH to about 7.0 can control *clubroot* disease in the cabbage family, because the spores of the fungal pathogen germinate poorly, if at all, under neutral to alkaline conditions.

Soil Nutrients. Healthy, vigorous plants usually can resist or outgrow diseases better than weaker plants, so provision of an optimal level of balanced nutrition is an important step in disease management. High levels of nitrogen fertilization tend to increase plants' susceptibility to fungal diseases; high levels of ammonium (as compared to nitrate) nitrogen especially increase wilt diseases caused by *Fusarium* fungi. On the other hand, high levels of nitrate (as compared to ammonium) tend to aggravate such diseases as potato scab, rice blast, wheat take-all, and corn stalk rot. Potassium fertilizers often reduce fungal disease severity, as do relatively high levels of calcium and manganese. Nutrient imbalances and micronutrient deficiencies can make plants especially susceptible to attack.

Organic Toxins. As an alternative to the use of synthetic, broad-spectrum synthetic fungicides or fumigants, certain natural organic antifungals can be introduced to the soil via microbial breakdown of organic amendments. An example is the rotation of cauliflower with broccoli such that the broccoli leaf residues left after harvest are tilled into the soil where they break down and release volatile compounds specifically toxic to the *Verticillium dahliae* fungus. This "biofumigation" can provide a level of disease control in the following cauliflower crop equal to that achieved by synthetic fumigants.

Soil Physical Properties. Soil compaction often aggravates fungal root diseases by slowing root growth, inducing more root excretions that attract the pathogens, and by promoting wet, poorly aerated conditions. Wet, cold soils favor some seed rots and seedling diseases such as *damping-off.* Good drainage and planting on ridges can help control these diseases. High soil temperature can be used to control a number of pathogens. **Solarization**, the use of sunlight to heat soil under clear plastic sheeting, is a practical way to partially sterilize the upper few cm of soil in some field situations. Steam or chemical sterilization is a practical method of treating greenhouse potting media. It should be remembered, however, that sterilization kills beneficial microorganisms, such as mycorrhizal fungi, as well as pathogens, and so may do more harm than good!

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Disease-Suppressive Soils[15]

Research on plant diseases ranging from *Phytophthora root rot* in eucalyptus forests to *Fusarium wilts* in banana plantations has documented the existence of **disease-suppressive soils**, an exceptional condition in which a disease fails to develop *even though both the virulent pathogen and a susceptible host are present.* The reason that certain soils become disease-suppressive is not entirely understood, but much evidence suggests that the pathogenic organisms are inhibited by **antagonism** from beneficial bacteria and fungi. Two broad types of disease suppression are recognized: general and specific.

General Suppression. General disease suppression is caused by high levels of overall microbial activity in a soil, especially at times critical in the development of a disease, such as when the pathogenic fungus is generating propagules or preparing to penetrate the plant cells. The presence of particular organisms is less important than the total level of activity. The mechanisms responsible for general suppression are thought to include: (1) competition by beneficial microorganisms in the rhizosphere for carbon (energy) sources, (2) competition for mineral nutrients (such as nitrogen and iron), (3) colonization and decomposition of pathogen propagules (e.g., spores), (4) antibiotic production by varied actinomycete and fungal populations (see Section 11.10), and (5) lack of suitable root infection sites due to surface colonization by beneficial bacteria (see Figure 11.39) or previous infection by beneficial mycorrhizal fungi. In natural systems, the highly organic litter layer often provides an environment of such high microbial activity that most pathogens cannot compete. In agricultural systems, general suppression can often be encouraged by the addition of large amounts of decomposable organic matter from composts, manures, and cover crop residues, and by developing a "litter layer" through no-till and mulching techniques.

Specific Suppression. Specific suppression is attributable to the actions of a single species or a narrow group of microorganisms that inhibit or kill a particular pathogen. The effective presence of the specific suppressing organism may result from the same types of organic matter management just described or from introduction of an inoculum containing high numbers of the desired organism.

In some cases, specific disease suppression has developed through long-term crop monoculture in which the buildup of the pathogen during the first few years is eventually overshadowed by a subsequent buildup of specific organisms antagonistic to the pathogen (Figure 11.43). The biological nature of the suppression is supported by the fact that adding a small amount of suppressive

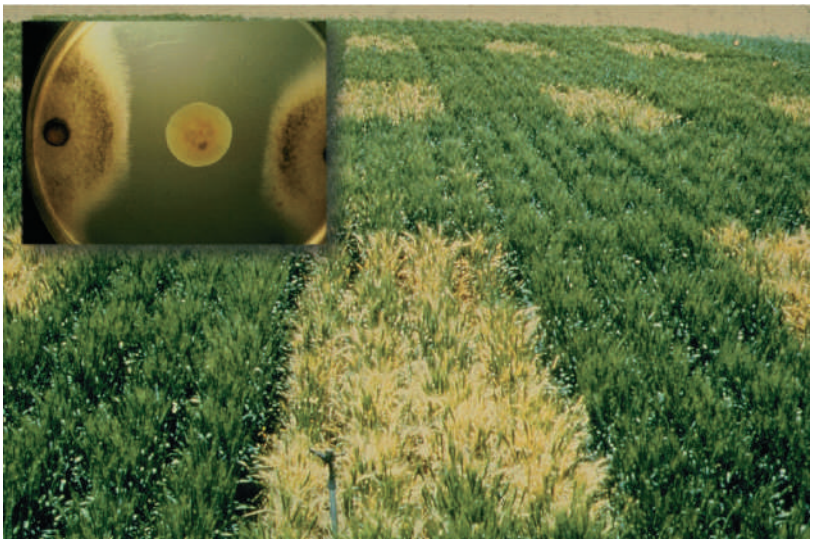

Figure 11.43 *Classic case of disease-suppressive soil. (Inset) A colony of a certain fluorescent Pseudomonas bacteria (center of plate) produces an antibiotic toxic to* Gaeumannomyces graminis *(the fungal pathogen that causes take-all disease), preventing the pathogen colonies from growing to the center of the plate. (Background) Plots in eastern Washington that grew monoculture wheat for 15 years and eventually developed high populations of a specific group of wheat rhizosphere bacteria, fluorescent Pseudomonas spp. These rhizobacteria produce an antifungal compound (2,4-diacetylphloroglucinol) that inhibits the take-all pathogen. In the 15th year of the study, the entire field was inoculated with* G. graminis *for experimental purposes, but the disease developed (seen as light-colored, prematurely desiccated plots) only where the soil was fumigated prior to the inoculation. The fumigation killed most of the antagonistic organisms, leaving the pathogenic fungi free to multiply and infect the wheat plants.* (U.S. government public domain photos by R. J. Cook of the USDA/ARS from an image collection on Biological Control of Plant Diseases published by the American Phytopathological Society)

[15]For an example of a molecular investigation of the mechanisms and organisms behind disease suppressiveness in soil, see Mendes et al. (2011).

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soil to the disease-conducive soil result in partial suppression, while partial heat sterilization of the suppressive soil killed most of the beneficial antagonistic organisms and resulted in loss of suppressiveness (Figure 11.44).

Specific organisms known to be antagonistic to pathogens include *Trichoderma viride* fungi and certain fluorescent *Pseudomonas* bacteria, which produce antibiotics specific against pathogens or produce compounds that bind so tightly with iron that the pathogen spores cannot get enough of this nutrient to germinate. Treating plant seeds with specific microbes that fend off seed rot pathogens may be one of the most practical applications of the inoculation approach (Box 11.4). Despite the existence of numerous commercial products containing beneficial microorganisms, we should remember the quote from Beijerinck (Section 11.10) and not place too much faith in the specific inoculation approach, because successful suppression is usually limited not by the absence of a particular organism, but by appropriate conditions that will stimulate the extremely high population densities of the organism needed for effective suppression.

Use of Composts. Horticulturalists have been able to control *Fusarium* diseases in containerized plants by replacing traditional potting mixes with growing media made mainly from certain well-aged **composts**. Apparently, large numbers of beneficial antagonistic organisms colonize the organic material during the final stages of composting (see Section 12.10), and the stabilized organic substrate stimulates the activity of indigenous beneficial organisms without stimulating the pathogens. Similar success in practical disease suppression has been experienced with the use of composted materials on turfgrass, especially for replacing peat (which is relatively inert and does not stimulate disease suppression) in topdressing golf course greens (see Figure 11.46).

Induced Systemic Resistance.[16] The role of soil ecology in protecting plants from disease is not limited to belowground infections. Beneficial rhizobacteria have an intriguing mode of action called **induced systemic resistance**, which helps plants ward off infection by diseases or insect pests both above and below ground. The process begins when a plant root system is colonized by beneficial rhizobacteria that cause the accumulation of a signaling chemical. The chemical signal is translocated up to the shoot, where it induces leaf cells to mount a chemical defense against a specific pathogen, even before the pathogen has arrived on the scene. When the pathogen (perhaps a fungal spore) does arrive on the leaf, its infection process is aborted almost before it can

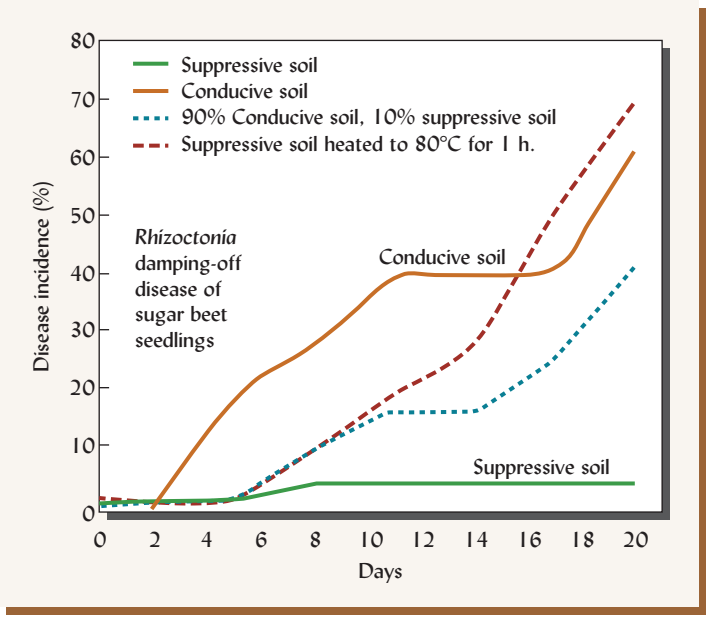

Figure 11.44 *Typical characteristics of a disease-suppressive soil. Sugar beet seedlings were grown in pots filled with sandy soil from a field in The Netherlands, parts of which had been observed to be suppressive of damping off, a fungal disease that can rapidly kill small seedlings. All the pots were inoculated with the disease-causing fungus, Rhizoctonia solani. The graph shows the percent of sugar beet seedlings that showed symptoms of the disease during the following 20 days. In the suppressive soil, less than 5% of the seedlings exhibited disease symptoms, while over 60% of the seedlings in the nonsuppressive (conducive) soil succumbed to the disease. Where the suppressive soil was partially heat-sterilized, the disease incidence was low for a few days, but within two weeks the disease was as bad as or worse in those pots than in the conducive soil. As is true in the field, sterilization kills most of the beneficial as well as pathogens organisms—but the pathogen population tends to grow back much faster. The biological nature of the suppressiveness is also supported by the fact that a mixture of 10% suppressive soil and 90% disease-conducive soil reduced the disease incidence by nearly half.* [Graphed from data in supplementary materials for Mendes et al. (2011)]

[16]For molecular and ecological insights into induced systemic resistance see Bakker et al. (2013).

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BOX 11.4

CHOOSING SIDES IN THE MICROBE WARS

Recent advances in our understanding of microbial ecology, combined with new techniques for enumerating and isolating microbial species, have opened many interesting and promising opportunities to harness the antagonisms long observed among microorganisms.

Seed treatments are now commercially available that use antagonistic soil bacteria instead of chemical fungicide to protect seed from rot-causing soil pathogens. Strains of Pseudomonas fluorescens have been specially selected and enhanced to respond to root signals, colonize the rhizosphere soil, and protect plant roots from soilborne diseases. When a preparation of these bacteria is applied as seeds are sown, the seeds germinate safely, even in soil known to be infested with seed-rotting fungi. Seeds sown without the treatment decay before they can germinate. Similar antagonistic organisms have been used for rot diseases in crops as varied as beans and tea bushes (Figure 11.45). Another approach is to select for plants that are most effective in sending out chemical signals that recruit protective bacteria to their rhizoplane to fend of attacking pathogens. Widespread use of such biologically based disease protection in the place of conventional fungicidal chemicals could reduce the loading of toxic compounds into the environment and avoid "killing the good with the bad" denizens of the soil.

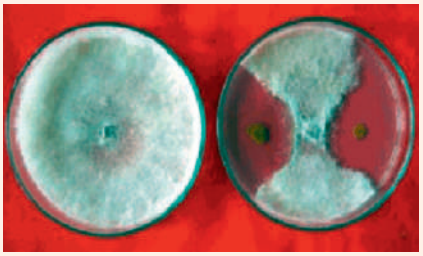

Figure 11.45 *Pseudomonas aeruginosa isolated from tea plantation soil in India was added to the ager plate on the right and showed biocontrol against the tea root pathogen Fomes lamoensis. The plate on the left shows the pathogen's growth without the P. aerufinosa.* [From Morang et al. (2012)]

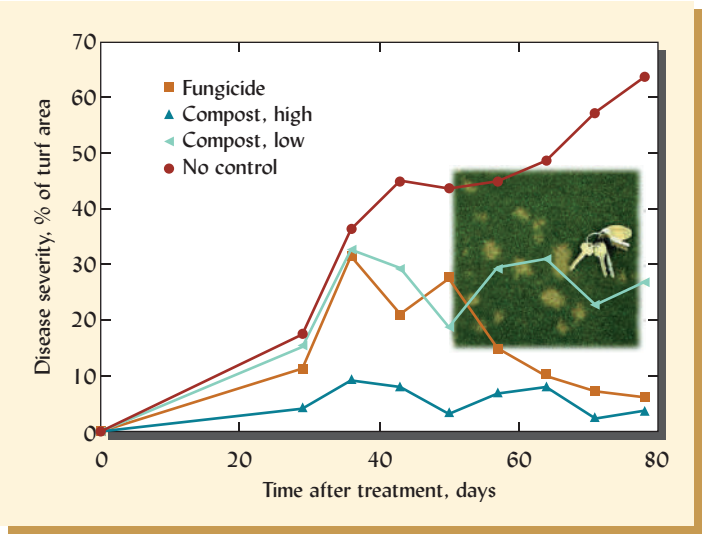

Figure 11.46 *Topdressing with compost as a nontoxic means of suppressing dollar spot disease on bentgrass putting greens (inset photo). The disease, caused by the fungus Sclerotinia homoeocarpa, was controlled as well or better by the high rate of compost (0.5 kg/m^2 topdressed every three weeks) as by the synthetic fungicide (Chlorthalonil, sprayed on every two weeks). Even the lower rate (0.1 kg/m^2) of compost provided some control of the disease. All the turfgrass plots were inoculated with the disease organism. The researchers suggest that topdressing with compost provided a general type of disease suppression since they found little difference among composts made from many different materials. The means from two years' data are shown.* (John Kaminski)

begin. In many cases studied so far on crop plants, the resistance-inducing organism has been a *Pseudomonas* or *Serratia* bacteria. In other cases, the arrival of a pathogen or pest on the plant shoot or root, induces the plant roots to release signaling compounds that attract beneficial rhizosphere bacteria that then stimulate the plant's immune system. Such mechanisms have been shown to effectively reduce damages by numerous fungal, bacterial, and viral pathogens and several leaf-eating insect pests.

These examples merely hint at the complexity of the plant–soil communities in Nature and the potential for controlling plant diseases and pests through ecological management rather than applications of toxic chemicals.

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11.14 ECOLOGICAL RELATIONSHIPS AMONG SOIL ORGANISMS

Mutualistic Associations

We have already mentioned a number of mutually beneficial associations between plant roots and other soil organisms (e.g., mycorrhizae and nitrogen-fixing nodules) and between several microorganisms (e.g., lichens). Other examples of such associations abound in soils. For example, photosynthetic algae reside within the cells of certain protozoans. We will now focus on several types of cyanobacterial–algal–fungal associations that are important components of desert ecosystems.

Biocrusts[17]

In relatively undisturbed arid- and semiarid-region ecosystems, where the vegetation cover is quite patchy, it is common to find an irregular, usually dark-colored crust covering the soil in the areas between clumps of grasses and shrubs. In many cases this forms a sort of miniature landscape of tiny, jagged pinnacles only a few centimeters tall (see Figure 11.47). This crust is not at all like the physical–chemical crusts associated with degraded soils that have a hard, smooth surface seal (see Section 4.6). Rather, the **biocrusts** of arid lands are intricate living systems that greatly benefit the associated natural vegetation communities. They consist of mutualistic associations that usually include algae or cyanobacteria along with fungi, mosses, bacteria, and/or liverworts. An intact microbiotic crust is considered a sign of a healthy ecosystem.

Such crusts provide considerable protection against erosion by wind and water by binding soil particles together, protecting the soil from raindrop impact, and increasing surface roughness, which reduces wind velocity. They also improve arid-region ecosystem productivity by: (1) helping to conserve and cycle nutrients, (2) increasing nitrogen supplies via the nitrogen-fixing activities of the cyanobacteria, (3) enhancing water supplies in some cases by

Figure 11.47 *Tiny pinnacles of a microbiotic crust seem to reflect the larger pinnacles of an arid landscape. These crusts consist of algae, cyanobacteria, fungi, and other organisms living mutualistically (Right) A scanning electron micrograph of cyanobacteria filaments that make up the crust's backbone. (Left) A crust on salty soils in semiarid Australia. Biocrusts cover the soil in unvegetated patches between clumps of desert shrubs and grasses, providing considerable protection against erosion by wind and water. They improve desert productivity by adding nitrogen and conserving water and nutrients. The fragile biocrusts can be easily destroyed by wheels, feet, and hooves.* (Jayne Belnap/USGS)

[17]Other names used to refer to these **biocrusts** include *microbiotic crusts*, *biological crusts*, *cryptograms*, *cryptobiotic crusts*, *microfloral crusts*, and *microphytic crusts*. All refer to the same thing. See Belnap (2003) for a brief overview and further reference citations on the ecology of microbial crusts. For an overview of technical review of scientific and practical knowledge about biocrusts, see Belnap (2013).

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increasing infiltration and reducing evaporation, and (4) contributing to net organic matter production by crust photosynthesis, which may continue during environmental conditions that inhibit photosynthesis by higher plants in the ecosystem. The filamentous cyanobacteria make a particularly important contribution to these functions, as they not only photosynthesize but also fix from 2 to 40 kg/ha of nitrogen annually and form sticky polysaccharide coatings or sheaths that catch nutrient-rich dust and bind soil particles. Unfortunately, the biocrusts can be easily destroyed by trampling or burial under windblown soil and are very slow to reestablish. Off-road vehicles, off-trail hiking, and overgrazing are especially damaging to these important ecosystem components.

Effects of Agricultural Practices on Soil Organisms

Changes in environment affect both the number and kinds of soil organisms. Clearing forests or grasslands for cultivation drastically changes the soil environment. Monocultures or even common two-crop rotations greatly reduce the number of plant species and so provide a much narrower range of plant materials and rhizosphere environments than nature provides in less managed ecosystems. Changing the crops grown, or even the choice of winter cover crop can have far reaching and long lasting impacts in the belowground community (see Figure 11.48).

While agricultural practices have different effects on different organisms, a few generalizations can be made (Table 11.8). For example, some agricultural practices (e.g., extensive tillage and monoculture) generally reduce the diversity of soil organisms as well as the abundance (number) of individuals. However, monoculture may *increase* the population of a few specially adapted species.

Adding lime and fertilizers (either organic or inorganic) to an infertile acid soil generally will increase microbial and fauna activity, largely due to the increase in the plant biomass that is likely to be returned to the soil as roots, root exudates, and shoot residues. Tillage, on the other hand, is a drastic disturbance of the soil ecosystem, disrupting fungal hyphae networks and earthworm burrows, as well as speeding the loss of organic matter. Reduced tillage therefore tends to increase the role of fungi at the expense of the bacteria and usually increases overall organism numbers as organic matter accumulates in the upper horizons (Table 11.9). Addition of animal manure or compost stimulates even higher microbial and faunal (especially earthworm) activity.

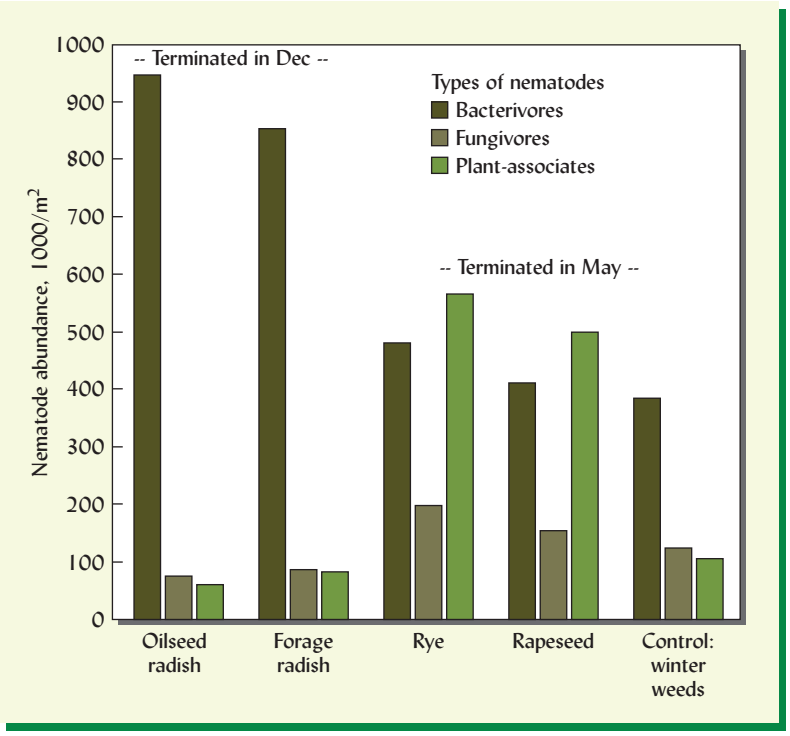

Figure 11.48 *Adding a winter cover crop changed the nature of the soil community under an agricultural field in Maryland, USA. In addition to the standard (control) practice of leaving the field fallow with only a few weeds growing during the winter, five different cover crops were planted in late summer. These included two types of radishes with large fleshy roots with high contents of sugars and antifungal compounds. These freeze-susceptible cover crops died in late December. The other two cover crops were winter hardy (the grass, cereal rye, and the Brassica, rapeseed) and so had to be terminated with a herbicide in early May. A corn crop was then planted across all the plots. In late August, some nine months after the radish died and four months after the rye and rapeseed were killed, the soil was found to be dominated by bacterivore nematodes where the radishes had been grown, while plant-associated nematodes and fungivores were much more prevalent in the other plots, suggesting a more fungi-dominated food web.* [Graphed from data in Gruver et al. (2010)]

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Table 11.8
Soil-Management Practices and the Diversity and Abundance of Soil Organisms
Practices that tend to enhance biological diversity and activity in soils are also those associated with efforts to make agricultural systems more sustainable.

Decreases biodiversity and populations	Increases biodiversity and populations
Fumigants	Proper fertilizer use
Nematicides	Lime on acid soils
Some insecticides and herbicides	Proper irrigation
Compaction	Improved drainage and aeration
Soil erosion	Animal manures and composts
Industrial wastes and heavy metals	Domestic (clean) sewage sludge
Intensive tillage	Reduced or zero tillage
Monocropping	Complex crop rotations
Row crops	Grass–legume pastures
Bare fallows	Cover crops or mulch fallows
Residue burning or removal	Residue return to soil surface
Plastic mulches	Organic mulches

Table 11.9
Effect of Tillage Systems on Biomass Carbon of Microbial and Faunal Groups in Soil
Researchers in Georgia, USA, grew grain sorghum in summer and a rye cover crop each winter on a sandy loam (Kanhapludults). With plow tillage, plant residues were mixed into the soil, but with no-till residues were left as surface mulch. Decomposer, microphytic feeder, and detritivore functions were dominated by larger organisms (fungi, microarthropods, and earthworms) in the no-till system, while smaller organisms (bacteria, protozoa, and nematodes) were more prominent in the plowed system.

	Carbon, kg/ha[a]							
				Nematodes				
Tillage	Fungi	Bacteria	Protozoa	Fungivores	Bacterivores	Microarthropods	Enchytraeids	Earthworms
No-till	360	260	24	0.14	0.82	1.31	5.55	60
Plowed	240	270	39	0.47	1.27	0.49	4.79	21

[a]Depth of sampling was 0–5 cm for microbes and arthropods, 0–21 cm for nematodes, 0–15 cm for worms. Calculated from data of various sources presented by Beare (1997).

Pesticides are highly variable in their effects on soil ecology (see Section 18.4). Soil fumigants and nematicides can sharply reduce organism numbers, especially for fauna, at least on a temporary basis. Use of herbicides often reduces biological diversity, mainly because they are so effective in eliminating weeds that otherwise would add more and diverse plant inputs. On the other hand, application of a particular pesticide often stimulates the population of specific microorganisms, either because the organisms can use the pesticide as food or, more likely, because the predators of that organism have been killed. Figure 11.49 illustrates how a management practice (insecticide application in this case) that affects one group of organisms will likely affect other groups as well and will eventually impact the productivity and functioning of the whole soil ecosystem. Such indirect and often surprising effects occur in all ecosystems. It is wise to remember that the interrelationships among soil organisms are intricate, and the effects of any perturbation of the system are difficult to predict.

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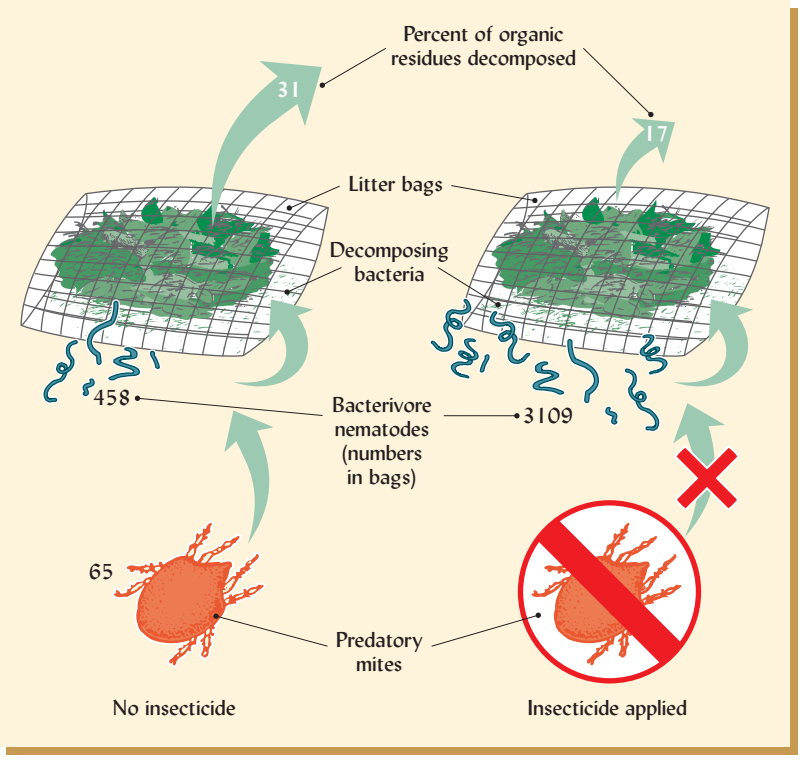

Figure 11.49 *The indirect effects of insecticide treatment on the decomposition of creosote bush litter in desert ecosystems. Litter bags filled with creosote bush leaves and twigs were buried in desert soils in Arizona, Nevada, and California in the United States, either with or without an insecticide (chlordane) treatment. The insecticide killed virtually all the insects and mites. Without predatory mites to hold them in check, bacterivore nematodes multiplied rapidly and devoured a large portion of the bacterial colonies responsible for litter decomposition and nutrient cycling. Thus, the insecticide reduced the rate of litter decomposition nearly in half, not by any direct effect on the bacteria, but by the indirect effect of killing the predators of their predators.* [Diagram courtesy of Ray R. Weil, based on data calculated from Whitford et al. (1982)]

Links Between Communities Above- and Belowground[18]

The communities of plants and animals we see aboveground greatly influence—and are profoundly influenced by—the communities belowground that we rarely see. The connections and interactions between them are both direct and indirect. Direct effects include the damage done to plants by pathogenic soil fungi, root-feeding nematodes, and the like. Direct effects also include the positive influences of mycorrhizae and beneficial rhizosphere bacteria, including those that cause the induced systemic resistance just described. Indirect effects include the complex feeding activities within the soil food web that eventually release nutrients that plants can use. In these and many other ways, the soil food web alters the types and productivity of plants in the aboveground world and, in so doing, affects the food supply and habitat for aboveground animals as well.

In turn, inputs from the aboveground communities influence the communities in the soil. From the beginning of this chapter (Figure 11.3) we have seen that the energy that drives the soil food web comes from aboveground photosynthesis via the organic carbon in plant litter, rhizodeposition, and herbivore excretions. Therefore, the numbers and activities of the belowground organisms are highly responsive to the amount of such inputs, especially plant litter. However, it should also be noted that the *type* and *quality* of plant litter produced by the aboveground community (see also Section 12.3) has an enormous impact on the abundances of the various creatures living in the soil (Table 11.10).

It is no wonder that ecologists are coming to recognize that ecosystems on land can be understood only when sufficient attention is paid to the world beneath the land's surface. For example, conservation biologists urgently need to learn what makes some exotic plants so invasive that they destroy native plant communities. It turns out that at least part of the answer may be found belowground in the community of organisms that colonize the plant rhizospheres (see Figure 11.50).

[18]For an introduction to how soil ecology influences plant invasiveness, see Wolfe and Klironomos (2005). For an authoritative treatise on the aboveground–belowground interactions, see Wardle (2002). For practical use of these relationships in restoring ecosystems, see Kardol and Wardle (2010).

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Table 11.10
Type of Forest Litter Influences the Abundances of Selected Faunal Groups
Leaves fallen from two species of forest plants were placed in mesh litter bags (100 g dry matter per bag) and pinned to the soil surface in a temperate forest in New Zealand. After 279 days the more nutrient-rich litter supported greater numbers of most faunal groups, except predatory nematodes. The activities of soil organisms will in turn influence the types and productivity of plants in the forest aboveground.

	Nutrients in litter, %		Numbers of organisms/litter bag			
Source of litter plant species	N	P	Microbial feeding nematodes	Predatory nematodes	Tardigrades	Coleoptera beetles
Metrosideno umbellata	0.35	0.03	6,600	210	35	4
Aristotelia serrata	2.94	0.24	12,800	73	670	364

Calculated from selected data in Wardle et al. (2006).

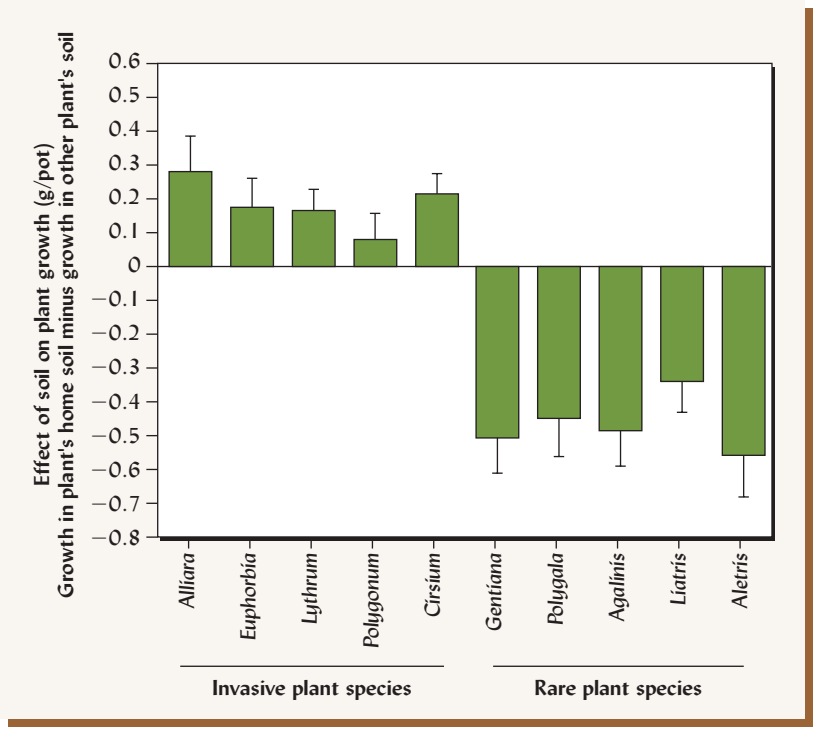

Figure 11.50 *Soil feedback responses help explain why some plants become invasive and others rare. Invasive plants (from Canadian grasslands) did well with soil in which they had already grown (their "home soil"). Rare plants did not. Research shows that certain plants quickly accumulate species-specific pathogenic fungi and bacteria in their rhizosphere, making these plants such weak competitors that they eventually become rare species. Other plants are strong competitors and become invasive because they avoid a rapid buildup of specific soil pathogens in their rhizosphere. The invasive plants may also efficiently exploit mycorrhizal fungi, even competing for nutrients by connecting to mycorrhizal hyphae already associated with neighboring plants' roots. This is but one example of how the ecology belowground can influence the diversity and productivity of plant species we see aboveground.* [Graph drawn from data in Klironomos (2002)]

11.15 CONCLUSION

The soil is a complex ecosystem with a highly diverse community of organisms that are vital to the cycle of life on Earth. As plant and animal tissues and compounds are added to the soil, the belowground community processes them, returning carbon dioxide to the atmosphere, where it can be recycled through plant photosynthesis. Simultaneously, the soil organisms use portions of these materials to create soil organic matter. During digestion of organic substrates, soil microbes and their predators release essential plant nutrients in inorganic forms that can be readily absorbed by plant roots or may be leached from the soil. The microbes also mediate the redox reactions that influence soil colors, nutrient cycling, and the production of gases that contribute to global warming.

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Animals, particularly earthworms, ants, and termites, mechanically incorporate residues into the soil and leave open channels through which water and air can flow. As such, they are examples of soil ecosystem engineers that change the soil environment for all its inhabitants and create niches in which other organisms can live.

Plants form a bridge connecting the above- and belowground worlds. Plant–soil systems are highly integrated and neither plants nor soil organisms would exist as we know them without the other. Just as humans carry with them and rely upon complex communities of microorganism in their gut and on their skin, plants stimulate and rely upon the complex community of microbes that have adapted to life in the rhizosphere. This zone of soil adjacent to plant roots is one of the most energy-rich and biologically diverse habitats on earth.

Certain rhizosphere microorganisms, such as mycorrhizal fungi and Rhizobia bacteria, form well-known symbiotic associations with certain plants, playing special roles in plant nutrition and nutrient cycling. However, scientific understanding is just beginning to scratch the surface of the complex root–microbes communities beneath our feet. Apparently the rhizosphere is filled with hundreds of specific chemical signaling compounds by which plant and microbes communicate with each other.

Plants use such signals to enlist the aid of soil fauna or microbes in fending off potential pests and pathogens. Numerous specific fungi and bacteria produce antibiotic compounds that help them compete, can rescue plants from disease-causing organisms, and form the basis for life-saving human drugs.

Microorganisms such as fungi, archaea, and bacteria are responsible for most organic decay, although their activity is greatly influenced by the soil fauna which physically shred the plant remains and provide transport and a suitable environment that enhances the function of many of the microbes. To obtain energy and nutrients, soil organisms break down plant litter. As they do so, they stabilize a portion as soil organic matter, and leave behind compounds that are useful to plants. Soil organic matter, its decomposition and influence on soil function are topics of the next chapter.

STUDY QUESTIONS

1. What is *functional redundancy*, and how does it help soil ecosystems continue to function in the face of environmental shocks such as fire, clear-cutting, or tillage?
2. In the example illustrated in Table 11.9, identify the organisms, if any, that play the roles of *primary producers*, *primary consumers*, *secondary consumers*, and *tertiary consumers*.
3. Describe some of the ways in which mesofauna play significant roles in soil metabolism even though their biomass and respiratory activity is only a small fraction of the total in the soil.
4. What are the four main types of metabolism carried out by soil organisms relative to their sources of energy and carbon?
5. What role does O_2 play in aerobic metabolism? What elements take its place under anaerobic conditions?
6. A *mycorrhiza* is said to be a symbiotic association. What are the two parties in this symbiosis, and what are the benefits derived by each party?
7. In what ways is soil improved as a result of earthworm activity? Are there possible detrimental effects as well?
8. What is the *rhizosphere*, and in what ways does the soil in the rhizosphere differ from the rest of the soil?
9. Explain and compare the effects of tillage and manure application on the abundance and diversity of soil organisms.
10. What is *induced systemic resistance*, and how does it work?
11. What is a disease-suppressive soil? Explain the difference between general and specific forms of suppression.
12. Discuss the value and limitations of using specific inoculants for (a) mycorrhizae and (b) disease suppression. For each type of inoculation, describe a situation for which the chances would be very good for improving plant growth.
13. What are the main food web roles played by nematodes and how can we visually (with a microscope) distinguish among nematodes that play these roles?
14. In what ways are Actinomycetes like other groups of bacteria, and in what ways are they special?
15. Through appropriate extractions and counting you determine that there are 58 nematodes in a 1-gram sample of soil. How many nematodes would occur in 1.0 m^2 area of this soil? In 1 hectare? Assume the samples came from the upper 10 cm of soil with a bulk density = 1.3 Mg/m^3.
16. Explain the concept of an *ecosystem engineer* with two soil examples.

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REFERENCES

Ackerman, I. L., W. G. Teixeira, S. J. Riha, J. Lehmann, and E. C. M. Fernandes. 2007. "The impact of mound-building termites on surface soil properties in a secondary forest of Central Amazonia." *Applied Soil Ecology* **37**:267–276.

Al-Karaki, G. N. 2006. "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water." *Scientia Horticulturae* **109**:1–7.

Alper, J. 1998. "Ecosystem 'engineers' shape habitats for other species." *Science* **280**:1195–1196.

Amador, J. A., and J. H. Gorres. 2005. "Role of the anecic earthworm *Lumbricus terrestris* L. in the distribution of plant residue nitrogen in a corn (zea mays)-soil system." *Applied Soil Ecology* **30**:203–214.

Anderson, A. N., and J. D. Majer. 2004. "Ants show the way down under: Invertebrates as bioindicators in land management." *Frontiers of Ecology and the Environment* **2**:291–298.

Bardgett, R. D. 2005. *The Biology of Soil: A Community and Ecosystem Approach (Biology of Habitats)*. Oxford University Press, Oxford, p. 254.

Bardgett, R. D., and W. H. van der Putten. 2014. "Belowground biodiversity and ecosystem functioning." *Nature* **515**:505–511.

Bakker, P. A. H. M., R. F. Doornbos, C. Zamioudis, R. L. Berendsen, and C. M. J. Pieterse. 2013. "Induced systemic resistance and the rhizosphere microbiome." *Plant Pathology Journal* **29**:136–143.

Baskin, Y. 2005. *Under Ground: How Creatures of Mud and Dirt Shape Our World*. Island Press, Washington, D.C., p. 237.

Beare, M. H. 1997. "Fungal and bacterial pathways of organic matter decomposition and nitrogen mineralization in arable soils." In L. Brussaard and R. Ferrera-Cerrato (eds.). *Soil Ecology in Sustainable Agricultural Systems*. Lewis Publishers, Boca Raton, FL.

Belnap, J. 2003. "The world at your feet: Desert biological soil crusts." *Frontiers of Ecology and the Environment* **1**:181–189.

Belnap, J. 2013. "Some like it hot, some not." *Science* **340**:1533–1534.

Biswas, J. C., J. K. Ladha, and F. B. Dazzo. 2000. "Rhizobia inoculation improves nutrient uptake and growth of lowland rice." *Soil Science Society of America Journal* **64**:1644–1650.

Blanco-Canqui, H., R. Lal, W. M. Post, R. C. Izaurralde, and M. J. Shipitalo. 2007. "Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio." *Soil Tillage Research* **92**:144–155.

Blouin, M., M. E. Hodson, E. A. Delgado, G. Baker, L. Brussaard, K. R. Butt, J. Dai, L. Dendooven, G. Peres, J. E. Tondoh, D. Cluzeau, and J. J. Brun. 2013. "A review of earthworm impact on soil function and ecosystem services." *European Journal of Soil Science* **64**:161–182.

Boulter, J. I., G. J. Boland, and J. T. Trevors. 2002. "Evaluation of composts for suppression of dollar spot (*Sclerotinia homoeocarpa*) of turfgrass." *Plant Disease* **86**:405–410.

Chander, Y., S. C. Gupta, S. M. Goyal, and K. Kumar. 2007. "Antibiotics: Has the magic gone?" *Journal of the Science of Food and Agriculture* **87**:739–742.

Chino, M. 1976. "Electron microprobe analysis of zinc and other elements within and around rice root growth in flooded soils." *Soil Science and Plant Nutrition Journal* **22**:449.

Coleman, D. C., D. A. J. Crossley, and P. F. Hendrix. 2004. *Fundamentals of Soil Ecology*. Elsevier Academic Press, London, p. 386.

de Vleeschauwer, D., and R. Lal. 1981. "Properties of worm casts under secondary tropical forest regrowth." *Soil Science* **132**:175–181.

D'Costa, V. M., K. M. McGrann, D. W. Hughes, and G. D. Wright. 2006. "Sampling the antibiotic resistome." *Science* **311**:374–377.

Edwards, C. A. (ed.). 2004. *Earthworm Ecology*. CRC Press, Boca Raton, FL, p. 448.

Edwards, C. A., and N. Q. Arancon. 2004. "Interactions among organic matter, earthworms and microorganisms in promoting plant growth." In F. Magdoff and R. R. Weil (eds.). *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL.

Eggleton, P. 2011. "An introduction to termites: Biology, taxonomy and functional morphology." In D. E. Bignell, et al. (eds.). *Biology of Termites: A Modern Synthesis*. Springer Netherlands, Amsterdam, pp. 1–26.

Eshel, A., and T. Beeckman (eds.). 2013. *Plant Roots: The Hidden Half*. CRC Press, Boca Raton, FL, pp. 1–848.

Fierer, N., A. S. Grandy, J. Six, and E. A. Paul. 2009. "Searching for unifying principles in soil ecology." *Soil Biology and Biochemistry* **41**:2249–2256.

Forsberg, K. J., A. Reyes, B. Wang, E. M. Selleck, M. O. A. Sommer, and G. Dantas. 2012. "The shared antibiotic resistome of soil bacteria and human pathogens." *Science* **337**:1107–1111.

Goheen, J., and T. Palmer. 2010. "Defensive plant-ants stabilize megaherbivore-driven landscape change in an African savanna." *Current Biology* **20**:1–5.

Griffiths, B. S., et al. 2000. "Ecosystem response of pasture soil community to fumigation-induced microbial diversity reductions: An examination of the biodiversity–ecosystem function relationship." *Oikos* **90**:279–294.

Gruver, L. S., R. R. Weil, I. A. Zasada, S. Sardanelli, and B. Momen. 2010. "Brassicaceous and rye cover crops altered free-living soil nematode community composition." *Applied Soil Ecology* **45**:1–12.

Hendrix, P. F., J. Mac, A. Callaham, J. M. Drake, C.-Y. Huang, S. W. James, B. A. Snyder, and A. W. Zhang. 2008. "Pandora's box contained bait: The global

FOR REFERENCE PURPOSES ONLY

problem of introduced earthworms." *Annual Review of Ecology, Evolution, and Systematics* 39:593–613.

Hiltpold, I., S. Toepfer, U. Kuhlmann, and T. Turlings. 2010. "How maize root volatiles affect the efficacy of entomopathogenic nematodes in controlling the western corn rootworm?" *Chemoecology* 20:155–162.

Hoeksema, J. D., V. B. Chaudhary, C. A. Gehring, N. C. Johnson, J. Karst, R. T. Koide, A. Pringle, C. Zabinski, J. D. Bever, J. C. Moore, G. W. T. Wilson, J. N. Klironomos, and J. Umbanhowar. 2010. "A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi." *Ecology Letters* 13:394–407.

Hoorman, J. J. 2011. "The role of soil protozoa and nematodes." Agriculture and Natural Resources Fact Sheet SAG-15-11. Ohio State University Extension, Columbus, OH. http://pnwboces.schoolwires.net/cms/lib03/NY24000991/Centricity/Domain/10/the%20role%20of%20soil%20nemotodes%20and%20protozoa%20%20OSU%20fact%20sheet.pdf

Hopfensperger, K. N., G. M. Leighton, and T. J. Fahey. 2011. "Influence of invasive earthworms on above and belowground vegetation in a northern hardwood forest." *The American Midland Naturalist* 166:53–62.

Huber, D. M., and S. Haneklaus. 2007. "Managing nutrition to control plant disease." *Landbauforschung Volkenrode* 57:313–322.

Jouquet, P., J. Dauber, J. Lagerlöfe, P. Lavelle, and M. Lepage. 2006. "Soil invertebrates as ecosystem engineers: Intended and accidental effects on soil and feedback loops." *Applied Soil Ecology* 32:153–164.

Kardol, P., and D. A. Wardle. 2010. "How understanding aboveground–belowground linkages can assist restoration ecology." *Trends in Ecology and Evolution* 25:670–679.

Kiers, E. T., M. Duhamel, Y. Beesetty, J. A. Mensah, O. Franken, E. Verbruggen, C. R. Fellbaum, G. A. Kowalchuk, M. M. Hart, A. Bago, T. M. Palmer, S. A. West, P. Vandenkoornhuyse, J. Jansa, and H. Bücking. 2011. "Reciprocal rewards stabilize cooperation in the mycorrhizal symbiosis." *Science* 333:880–882.

Klironomos, O. N. 2002. "Feedback with soil biota contributes to plant rarity and invasiveness in communities." *Nature* 417:67–70.

Kumar, K., S. C. Gupta, S. K. Baidoo, Y. Chander, and C. J. Rosen. 2005. "Antibiotic uptake by plants from soil fertilized with animal manure." *Journal of Environmental Quality* 34:2082–2085.

Lavelle, P., D. Bignell, M. Lepage, V. Wolters, P. Roger, P. Ineson, O. W. Heal, and S. Dhillion. 1997. "Soil function in a changing world: The role of invertebrate ecosystem engineers." *European Journal of Soil Biology* 33:159–193.

Ling, L. L., T. Schneider, A. J. Peoples, A. L. Spoering, I. Engels, B. P. Conlon, A. Mueller, T. F. Schaberle, D. E. Hughes, S. Epstein, M. Jones, L. Lazarides, V. A. Steadman, D. R. Cohen, C. R. Felix, K. A. Fetterman, W. P. Millett, A. G. Nitti, A. M. Zullo, C. Chen, and K. Lewis. 2015. "A new antibiotic kills pathogens without detectable resistance." *Nature* advance online publication.

Litterick, A. M., and L. Harrier. 2004. "The role of uncomposted materials, composts, manures, and compost extracts in reducing pest and disease incidence and severity in sustainable temperate agricultural and horticultural crop production: A review." *Critical Reviews in Plant Sciences* 23:453–479.

Lubbers, I. M., K. J. v. Groenigen, S. J. Fonte, J. Six, L. Brussaard, and J. W. v. Groenigen. 2013. "Greenhouse-gas emissions from soils increased by earthworms." *Nature Climate Change* 3:187–194.

McNear Jr., D. H. 2013. "The rhizosphere - roots, soil and everything in between." *Nature Education Knowledge* 4:7.

Mellon, M., C. Benbrook, and K. L. Benbrook. 2001. *Hogging It: Estimates of Antimicrobial Abuse in Livestock*. Union of Concerned Scientists, Cambridge, MA. www.ucsusa.org/publications.

Mendes, R., M. Kruijt, I. de Bruijn, E. Dekkers, M. van der Voort, J. H. M. Schneider, Y. M. Piceno, T. Z. DeSantis, G. L. Andersen, P. A. H. M. Bakker, and J. M. Raaijmakers. 2011. "Deciphering the rhizosphere microbiome for disease-suppressive bacteria." *Science* 332:1097–1100.

Miles, C., C. Blethen, R. Gaugler, D. Shapiro-Ilan, and T. Murray. 2012. *Using Entomopathogenic Nematodes for Crop Insect Pest Control*. Washington State University, Pullman, WA. http://cru.cahe.wsu.edu/CEPublications/PNW544/PNW544.pdf.

Nardi, J. B. 2007. *Life in the Soil: A Guide for Naturalists and Gardeners*. University of Chicago Press, Chicago, p. 336.

Neher, D. A. 2010. "Ecology of plant and free-living nematodes in natural and agricultural soil." *Annual Review of Phytopathology* 48:371–394.

Paul, E.A. 2014. *Soil Microbiology, Ecology and Biochemistry*. 4th ed. Academic Press, San Diego, 600 p.

Pehrsson, E.C., K.J. Forsberg, M.K. Gibson, S. Ahmadi, and G. Dantas. 2013. Novel resistance functions uncovered using functional metagenomic investigations of resistance reservoirs. *Frontiers in Microbiology* 4:145.

Reynolds, L. B., J. W. Potter, and B. R. Ball-Coelho. 2000. "Crop rotation with *Tagetes* sp. is an alternative to chemical fumigation for control of root-lesion nematodes." *Agronomy Journal* 92:957–966.

Sanders, D., and F. J. F. van Veen. 2011. "Ecosystem engineering and predation: The multi-trophic impact of two ant species." *Journal of Animal Ecology* 80:569–576.

Sileshi, G. W., M. A. Arshad, S. Konaté, and P. O. Y. Nkunika. 2010. "Termite-induced heterogeneity in African Savanna vegetation: Mechanisms and patterns." *Journal of Vegetation Science* 21:923–937.

Smith, S. E., and D. J. Read. 2008. *Mycorrhizal Symbiosis*, 3rd ed. Academic Press, San Diego, CA, p. 800.

Sota, T., S. Yamamoto, J.R. Cooley, K.B.R. Hill, C. Simon, and J. Yoshimura. 2013. "Independent divergence of 13- and 17-y life cycles among three periodical cicada

FOR REFERENCE PURPOSES ONLY

lineages." *Proceedings of the National Academy of Sciences* **110**: 6919–6924.

Stadler, B., A. Schramm, and K. Kalbitz. 2006. "Ant-mediated effects on spruce litter decomposition, solution chemistry, and microbial activity." *Soil Biology Biochemistry* **38**:561–572.

Stamets, P. 2005. *Mycelium Running: How Mushrooms Can Help Save the World*. Ten Speed Press, Berkeley, CA, p. 339.

Stone, A. G., S. J. Scheuerell, and H. M. Darby. 2004. "Suppression of soil-borne fungal diseases in field agricultural systems: Organic matter management, cover cropping, and cultural practices." In F. Magdoff and R. R. Weil (eds.). *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL.

Sylvia, D. M., J. J. Fuhrmann, P. G. Hartel, and D. A. Zuberer. 2005. *Principles and Applications of Soil Microbiology*. Prentice Hall, Upper Saddle River, NJ, p. 640.

Tate, R. L., III. 2009. *Soil Microbiology*. 3rd ed. John Wiley, New York, p. 500.

Torsvik, V. L. 1980. "Isolation of bacterial DNA from soil." *Soil Biology and Biochemistry* **12**:15–21.

Torsvik, V., L. Ovreas, and T. F. Thingstad. 2002. "Prokaryotic diversity—Magnitude, dynamics, and controlling factors." *Science* **296**:1064–1066.

USDA/NRCS. 2000. "Soil biology primer." Rev. Ed. [Online]. Soil and Water Conservation Society. Available at soils.usda.gov/sqi/concepts/soil_biology/biology.html (posted 18 June 2007; verified 1 July 2013).

Wardle, D. A. 2002. *Communities and Ecosystems: Linking the Aboveground and Belowground Components*. Princeton University Press, Princeton, NJ.

Wardle, D. A., G. W. Yeates, G. M. Barker, and K. I. Bonner. 2006. "The influence of plant litter diversity on decomposer abundance and diversity." *Soil Biology Biochemistry* **38**:1052–1062.

Weil, R. R., and W. Kroontje. 1979. "Organic matter decomposition in a soil heavily amended with poultry manure." *Journal of Environmental Quality* **8**:584–588.

Whitford, W. G., D. W. Freckman, P. F. Santos, N. Z. Elkins, and L. W. Parker. 1982. "The role of nematodes in decomposition in desert ecosystems." In D. Freckman (ed.). *Nematodes in Soil Ecosystems*. University of Texas Press, Austin, TX, pp. 98–116.

Wolfe, B. E., and J. N. Klironomos. 2005. "Breaking new ground: Soil communities and exotic plant invasion." *BioScience* **55**:477–487.

Wu, T., E. Ayres, R. D. Bardgett, D. H. Wall, and J. R. Garey. 2011. "Molecular study of worldwide distribution and diversity of soil animals." *Proceedings of the National Academy of Sciences* **108**:17720–17725.

Yang, L. H. 2004. "Periodical cicadas as resource pulses in North American forests." *Science* **306**:1565–1567.

Zamioudis, C., P. Mastranesti, P. Dhonukshe, I. Blilou, and C. M. J. Pieterse. 2013. "Unraveling root developmental programs initiated by beneficial pseudomonas spp. bacteria." *Plant Physiology* **162**:304–318.

Zhu, Y.-G., T. A. Johnson, J.-Q. Su, M. Qiao, G.-X. Guo, R. D. Stedtfeld, S. A. Hashsham, and J. M. Tiedje. 2013. "Diverse and abundant antibiotic resistance genes in Chinese swine farms." *Proceedings of the National Academy of Sciences* **110**:3435–3440.

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12 Soil Organic Matter

Their host consumed, themselves in death
Their substance too return to earth.
The forest thus sustains its wealth
And turns decay to surging life
—*Caroline Preston* (Natural Resources Canada)

Carbon accumulates in a forest soil. (Ray R. Weil)

In most soils, the percentage of soil organic matter[1] (SOM) is small, but its effects on soil function are profound. This ever-changing soil component exerts a dominant influence on many soil physical, chemical, and biological properties and ecosystem functions of soils. Soil organic matter provides much of the soil's cation exchange capacity (CEC) (discussed in Chapter 8) and water-holding capacity (Chapter 5). Certain components of soil organic matter are largely responsible for the formation and stabilization of soil aggregates (Chapter 4). Soil organic matter also contains large quantities of plant nutrients and acts as a slow-release nutrient storehouse, especially for nitrogen (Chapter 13). Furthermore, organic matter supplies energy and body-building constituents for most of the organisms whose nature and activities were discussed in Chapter 11. In addition to enhancing plant growth through the just-mentioned effects, certain organic compounds found in soils have direct growth-stimulating effects on plants. For all these reasons, the quantity and quality of soil organic matter are central in determining **soil quality** (Chapter 20).

Soil organic matter is a complex and varied mixture of organic substances. All organic substances, by definition, contain the element **carbon**, and, on average, carbon comprises about half of the mass of soil organic matter. Organic matter in the world's soil profiles contains four to six times as much carbon as is found in all the world's vegetation. Soil organic matter, therefore, plays a critical role in the global carbon balance—a balance that largely controls **global climate change**.

We will first examine the role of soil organic matter in the **global carbon cycle** and the process of **decomposition** of organic materials in soils. Next, we will focus on inputs and losses with regard to soil carbon in specific ecosystems. Finally, we will study the processes and consequences involved in soil organic matter management.

12.1 THE GLOBAL CARBON CYCLE

The element *carbon* is the foundation of all life. From cellulose to chlorophyll, the compounds that comprise living tissues are made of carbon atoms arranged in chains or rings and associated with many other elements. The cycle of carbon on Earth is the story of life

[1]For a broad review of the nature, function, and management of organic matter in agricultural soils, see Magdoff and Weil (2004). For a comprehensive collection of scientific treatises on the functions of organic matter in soils, sediments and other environmental systems, as well as information on the analysis of organic matter by modern instrumental techniques, see Sensi et al. (2009).

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on this planet. The carbon cycle is all-inclusive because it involves the soil, higher plants of every description, and all animal life, including humans. Disruption of the carbon cycle would mean disaster for all living organisms (Box 12.1).

Basic Processes

The basic processes involved in the global carbon cycle are shown in Figure 12.3. Plants take in carbon dioxide from the atmosphere. Then, through the process of photosynthesis, the

BOX 12.1

CARBON CYCLING—UP CLOSE AND PERSONAL

Imagine that you were one of the eight biospherians living a scientific game of survival in Biosphere 2, a giant 1.3-ha sealed glass building in the Arizona desert in the United States (Figure 12.1). Biosphere 2 contained a miniature ocean, coral reef, marsh, forest, and farm in a self-contained, self-supporting ecosystem in which the biospherians could live as part of the ecosystem they were studying. Instruments throughout the structure constantly monitored environmental parameters. What a great physical model (rather than a computer model) to study how a balanced ecosystem *really* works!

But it didn't take long for trouble to develop. First, the biospherians found it was no easy task to grow all the food they needed (Figure 12.2). Dependent on their meager harvests, they began to lose weight. Then, as if slowly starving were not bad enough, they soon began feeling short of breath. Instruments showed the oxygen level of the air was falling from its normal 21% to levels typical of high mountaintops (it eventually fell to as low as 14.2%). But unlike in "thin" air at high elevations, the carbon dioxide content of the air was rising. This wasn't supposed to be happening. Weren't all the green plants supposed to *use up* the carbon dioxide and *replenish* the oxygen supply? Unusual changes began talking place in the biosphereans' blood chemistry and metabolism—changes eerily like those of a bear in hibernation (during which both oxygen and food are limited). Eventually, the atmosphere became so low in oxygen and high in carbon dioxide that engineers had to give up on the "fully self-contained" aspect of the project and pump in oxygen and remove carbon dioxide from the air.

What had they overlooked? It turned out that the ecosystem was thrown out of kilter by the organic-matter-rich soil hauled in for the Biosphere farm. The soil, made from a mixture of pond sediment (1.8% C), compost (22% C), and peat moss (40% C), was installed uniformly about 1 m deep. This artificial soil contained about 2.5% organic C at all depths—far more than the 0.5% C or less expected in a typical desert soil. Had the designers read this book, they would have understood that peat might be stable in a boreal wetland (cool and anaerobic), but that aerobic soil microorganisms would rapidly use up oxygen and give off carbon dioxide as they metabolized organic matter in warm, moist garden soil aerated by tillage (see Section 12.2). This tale reminds us of the importance of soils in cycling C within the real biosphere of Earth! [For more on Biosphere 2, see: http://www.biospheres.com/, Torbert and Johnson (2001) and Walford (2002).]

Figure 12.1 *The Biosphere 2 structure, a huge, sealed, ecological laboratory.* (Photo by C. Allen Morgan. © 1995 by Decisions Investments Corp. Reprinted with permission)

Figure 12.2 *Biospherians at work growing their own food supply in the intensive agriculture biome with compost-amended soils rich in organic matter.* (Photo by Pascale Maslin. © 1995 by Decisions Investments Corp. Reprinted with permission)

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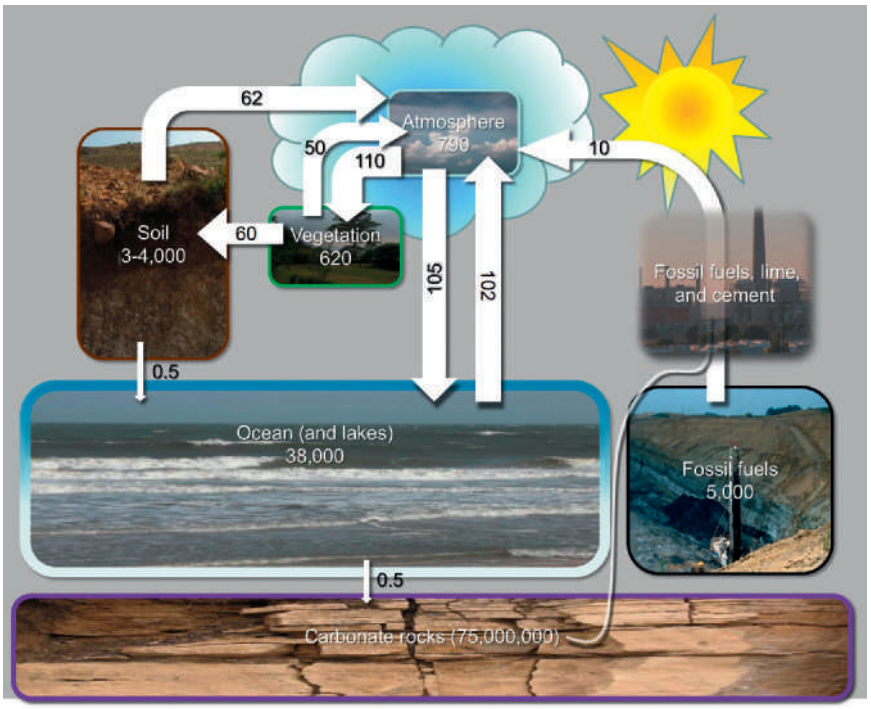

Figure 12.3 *The global carbon cycle emphasizing those pools of carbon which interact with the atmosphere. The numbers in boxes indicate petagrams (Pg = 10^{15} g) of carbon stored in the major pools. The numbers by arrows show amounts of carbon annually flowing (Pg/yr) by various processes between the pools. Note that the soil contains almost twice as much carbon as the vegetation and the atmosphere combined. Imbalances caused by human activities can be seen in the flow of carbon to the atmosphere from fossil fuel burning (7.5) and in the fact that more carbon is leaving (62 + 0.5) than entering (60) the soil. These imbalances are only partially offset by increased absorption of carbon by the oceans. The end result is that some 225 Pg/yr enters the atmosphere while only 215 Pg/yr of carbon is removed. It is easy to see why carbon dioxide levels in the atmosphere are rising.* [Data from IPCC (2007) and Pan et al. (2011); soil carbon estimate from Batjes (1996), Haddix et al. (2011), Lal (2012)]

energy of sunlight is trapped in the carbon-to-carbon bonds of organic molecules (such as those described in Section 12.2). Some of these organic molecules are used as a source of energy (via respiration) by the plants themselves (especially by the plant roots), with the carbon being returned to the atmosphere as carbon dioxide. The remaining organic materials are stored temporarily as constituents of the standing vegetation, most of which is eventually added to the soil as plant litter (including crop residues) or root deposition (see Section 11.7). Some plant material may be eaten by animals (including humans), in which case about half of the consumed carbon is exhaled into the atmosphere as carbon dioxide. The carbon not returned to the atmosphere is eventually returned to the soil as bodily wastes or body tissues. Once deposited on or in the soil, these plant or animal tissues are metabolized (digested) by soil organisms, which gradually return this carbon to the atmosphere as carbon dioxide.

Carbon dioxide also reacts in the soil to produce carbonic acid (H_2CO_3) and the carbonates and bicarbonates of calcium, potassium, magnesium, and sodium. The bicarbonates are readily soluble and may be removed in drainage. The carbonates, such as calcite ($CaCO_3$), are much less soluble and tend to accumulate in soils under alkaline conditions. Although this chapter focuses on the organic C in soils, the inorganic C content of soils (mainly as carbonates) may be substantial, especially in arid regions (Table 12.1). Eventually, as with the C in soil organic matter, most of the bicarbonate C and some of the carbonate C in soils is returned to the atmosphere as CO_2.

Some of the partially decomposed plant tissues and microbial cell debris is adsorbed onto soil colloid surfaces or occluded inside soil aggregates where it is protected from further microbial metabolism for decades or even centuries before the carbon in them is returned to the atmosphere as carbon dioxide. Such protection from decay allows organic matter to accumulate in soils.

Carbon Sources

The original source of soil organic matter is plant tissue, and the amount of organic matter accumulated in soils is partly a function of the net plant productivity that provides this material. Animals are secondary sources of organic matter. As they eat the original plant tissues, they contribute waste products, and they leave their own bodies when they

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die (review Figure 11.1). Certain forms of animal life, especially earthworms, termites, ants, and dung beetles, also play an important role in the incorporation and translocation of organic residues.

Globally, at any one time, approximately 3000 petagrams (Pg or 10^{15}g) of carbon are stored in soil profiles as soil organic matter (excluding surface litter), about one-third of that at depths below 1 m. An additional 940 Pg are stored in the upper 1 m of soil as carbonates that can release CO_2 upon weathering (as with organic C, there are significant additional stores of carbonate C below 1 m). Altogether, more than twice as much carbon is stored in the soil as in the world's vegetation and atmosphere *combined* (see Figure 12.1). Of course, this carbon is not equally distributed among all types of soils (Table 12.1). About half of the total organic carbon is contained in soils of just three orders, Histosols, Inceptisols, and Gelisols. Histosols (and Histels in the order Gelisols) are of limited extent but contain very large amounts of organic matter per unit land area. In fact, because many Gelisols consist of organic matter accumulations several meters thick, evidence now suggests that there may be much more carbon in this order than previously thought (see note b under Table 12.1)—perhaps as much as all other soil orders combined! Inceptisols (and nonhistic Gelisols) contain only moderate concentrations of carbon, but cover vast areas of the globe. The reasons for the varying amounts of organic carbon in different soils will be detailed in Section 12.8.

Table 12.1
MASS OF ORGANIC AND INORGANIC CARBON IN THE UPPER 1 M OF THE WORLD'S SOILS
Inorganic carbon is present mainly as calcium carbonates in soils of dry regions. Wetland soils as a group contain about 500 Pg of organic C, some 30.3% of the total organic C in global soils. Values for the upper 1 m represent 60–90% of the carbon in most soil profiles. Considerable additional C is stored in soil layers deeper than 1 m, especially in Gelisols and Histosols.

		Global carbon[a] in upper 100 cm			
		Organic	Inorganic	Total	
Soil order	Global area, 10^3 km^2		Pg		Total % of global Soil[c]
Entisols	21,137	90	263	353	14.2
Inceptisols	12,863	190	34	224	9.0
Histosols	1,526	179	0	180	7.2
Andisols	912	20	0	20	0.8
Gelisols	11,260	316[b]	7	323	12.9
Vertisols	3,160	42	21	64	2.6
Aridisols	15,699	59	456	515	20.6
Mollisols	9,005	121	116	237	9.5
Spodosols	3,353	64	0	64	2.6
Alfisols	12,620	158	43	201	8.0
Ultisols	11,052	137	0	137	5.5
Oxisols	9,810	126	0	126	5.1
Misc. land	18,398	24	0	24	1.0
Total	130,795	1,526	940	2,468	100.0

[a]Soil organic matter values may be estimated as 2.0 times soil organic carbon, although the multiplier traditionally used is 1.72. Organic nitrogen may also be estimated from organic carbon values by dividing by 12 for most soils, but see Section 12.3. Pg = Petagram = 10^{15} g.

[b]The value for Gelisols is likely an underestimate. Evidence-based estimates in Harden et al. (2012) range up to 1800 Pg organic C in Gelisols to a 3-m depth.

[c]Data selected from Eswaran et al. (2000).

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In a mature natural ecosystem or a stable agroecosystem, the release of carbon as carbon dioxide by oxidation of soil organic matter (mostly by microbial respiration) is balanced by the input of carbon into the soil as plant residues (and, to a far smaller degree, animal residues). However, as discussed in Section 12.8, certain perturbations of the system, such as deforestation, some types of fires, tillage, and artificial drainage, result in a net loss of carbon from the soil system.

Figure 12.3 shows that, globally, the release of carbon from soils into the atmosphere is about 62 Pg/yr, while only about 60 Pg/yr enter the soils from the atmosphere via plant residues. This imbalance of about 2 Pg/yr, along with about 10 Pg/yr of carbon released by the burning of fossil fuels (for energy) and limestone rock (to make cement) is only partially offset by increased absorption of atmospheric carbon dioxide by the ocean. Fossil fuel burning and degrading land-use practices have increased the concentration of carbon dioxide in the atmosphere at an accelerating rate since the beginning of the industrial revolution, some 400 years ago. The levels have increased from 290 to 400 ppm during the past century alone. The implications of carbon dioxide imbalances and of other gaseous emissions on climate change (the greenhouse effect) will be discussed in Section 12.9, after we consider the processes by which carbon cycles in the plant–soil–atmosphere system.

12.2 ORGANIC DECOMPOSITION IN SOILS

Because plant residues are the principal material undergoing decomposition in soils and, hence, are the primary source of soil organic matter, we will begin by considering the makeup of these materials.

Composition of Plant Residues

Green plant tissues contain from 60 to 90% water by weight (Figure 12.4). If plant tissues are dried to remove all water, analysis of the *dry matter* remaining shows that, on a mass basis, the dry matter consists mostly (at least 90–95%) of carbon, oxygen, and hydrogen.

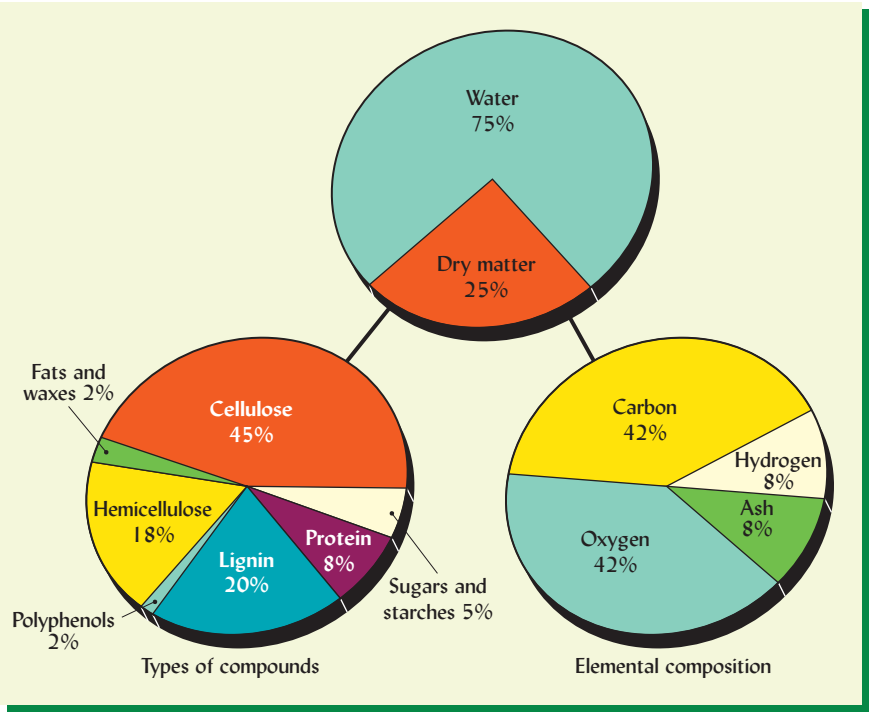

Figure 12.4 *Typical composition of representative green-plant materials. The major types of organic compounds are indicated at left and the elemental composition at right. The ash is considered to include all the constituent elements other than carbon, oxygen, and hydrogen (nitrogen, sulfur, calcium, etc.).*

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During photosynthesis, plants obtain these elements from carbon dioxide and water. If plant dry matter is burned (oxidized), these elements become carbon dioxide and water once more. Of course, some ash and smoke will also be formed upon burning, accounting for the remaining 5–10% of the dry matter. In the ash and smoke can be found the many nutrient elements originally taken up by the plants from the soil. Even though these elements are present in relatively small quantities, they play a vital role in plant and animal nutrition and in meeting the requirements of microorganisms. The essential nutrient elements found in the ash, such as nitrogen, sulfur, phosphorus, potassium, and micronutrients, will be given detailed consideration in later chapters.

Organic Compounds in Plant Residues. The organic compounds in plant tissue can be grouped into broad classes. Although representative percentages of these classes are shown in Figure 12.4, tissues from different plant species, as well as from different parts (leaves, roots, stems, etc.) of a given plant differ considerably in their makeup. Carbohydrates range from highly bioavailable simple sugars and starches to less easily broken down cellulose. As a group, carbohydrates are usually the most plentiful of plant organic compounds. Certain plant parts, especially seeds and leaf coatings contain significant amounts of fats, oils and waxes, some of which decompose rather slowly because of their highly water-repellent nature. Roots are especially significant as sources of soil organic matter and tend to decompose more slowly than shoot tissues.

Lignins, complex compounds with multiple ring-type or *phenol* structures, are components of plant cell walls. The content of lignin increases as plants mature and is especially high in woody tissues. Other **polyphenols**, such as tannins, may comprise as much as 6 or 7% of the leaves, root, and bark of certain plants (e.g., the brown color of steeped tea is due to tannins as are the brown leaf prints left by wet oak leaves on concrete sidewalks). In many types of tree leaves, much of the cellulose is encased in lignin. Lignin is often observed to decompose much more slowly than other litter components, as relatively few microbes can produce the necessary enzymes to break it down.

Proteins contain about 16% nitrogen and smaller amounts of other essential elements, such as sulfur, manganese, copper, and iron. Simple proteins decompose and release their nitrogen easily, while complex crude proteins are more resistant to breakdown.

Rate of Decomposition. Organic compounds may be listed in terms of ease of decomposition as follows:

1. Sugars, starches, and simple proteins — Rapid decomposition
2. Crude proteins
3. Hemicellulose
4. Cellulose
5. Fats and waxes
6. Lignins and phenolic compounds — Very slow decomposition

Decomposition of Organic Compounds in Aerobic Soils

Decomposition involves the breakdown of large organic molecules into smaller, simpler components. When organic tissue is added to an aerobic soil, four general processes take place: oxidation, release, synthesis, and protection. Although in most cases mechanical shredding by soil fauna or physical processes must occur before these processes can efficiently take place, the reactions themselves result mainly from microbial activity.

1. Plant carbon compounds are enzymatically *oxidized* to produce carbon dioxide, water, energy, and decomposer biomass.
2. Essential nutrient elements such as nitrogen, phosphorus, and sulfur are *released* and/or immobilized by a series of specific reactions that are relatively unique for each element.

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3. New compounds are *synthesized* by microbes as cellular constituents or as breakdown products or secondary metabolites.
4. Some of the original plant compounds, their breakdown products and microbial compounds become physically or chemical *protected* from further microbial decay via interactions with the soil environment.

Decomposition: An Oxidation Process. In a well-aerated soil, all of the organic compounds found in plant residues are subject to oxidation. Since the organic fraction of plant materials is composed largely of carbon and hydrogen, the oxidation of the organic compounds in soil can be represented as:

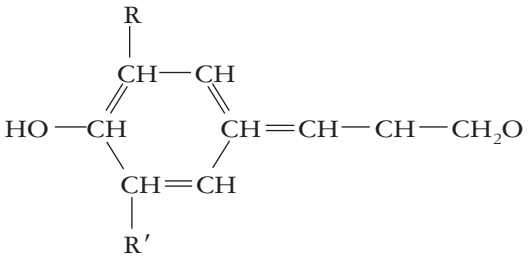
$$\underset{\substack{\text{Carbon- and}\\\text{hydrogen-containing}\\\text{compounds}}}{\text{R—(C, 4H)}} + 2O_2 \xrightarrow[\text{oxidation}]{\text{Enzymatic}} CO_2\uparrow + 2H_2O + \text{energy (478 kJ mol}^{-1}\text{ C)} \tag{12.1}$$

Many intermediate steps are involved in this overall reaction, and it is accompanied by important side reactions that involve elements other than carbon and hydrogen. Even so, this basic reaction accounts for most of the organic matter decomposition in the soil, as well as for the oxygen consumption and CO_2 release.

Breakdown of Cellulose and Starch. Cellulose and starch are polysaccharides—long chains (polymers) of sugar molecules. Enzymatic degradation proceeds in steps: first the long chains are broken down by rather specialized organisms into short chains, then into individual sugar (glucose) molecules, which many different organisms can metabolize as in Eq. (12.1). Cellulose is the most abundant polysaccharide on the Earth. Because the C—O—C chemical bonds linking the sugar molecules of cellulose together are much more difficult to break than those in starch, the initial chain-breaking step in cellulose decomposition requires the activity of specialized organisms that produce the enzyme *cellulase*.

Breakdown of Proteins. Plant proteins also succumb to microbial decay, yielding not only carbon dioxide and water, but amino acids such as glycine (CH_2NH_2COOH) and cysteine ($CH_2HSCHNH_2COOH$). In turn, these nitrogen and sulfur compounds are further broken down, eventually yielding such simple inorganic ions as ammonium (NH_4^+), nitrate (NO_3^-), and sulfate (SO_4^{2-}), forms readily available for plant nutrition.

Breakdown of Lignin. Lignin molecules are very large and complex, consisting of hundreds of interlinked phenolic ring subunits, most of which are phenylpropene-like structures with various methoxyl (—OCH_3) groups attached (shown here as R or R′):



Because the linkages among these structures are so varied and strong, only a few microorganisms (mainly *white rot fungi*, Figure 11.30) can break them down. Lignin is traditionally thought of as highly resistant to decomposition by most microbes, especially in the initial stages of decay. However research suggests that lignin will actually degrade in the early stages of decomposition as long as the supply of readily bioavailable carbon is great enough to fuel the production of lignin-degrading enzymes. In the field, lignin decomposition is also assisted

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by the physical activities of soil fauna. Once the lignin subunits are separated, many types of microorganisms participate in their breakdown. Still, much of the stable organic matter found in soils consists of lignin and lignin-like compounds.

Example of Organic Decay

The process of organic decay in time sequence is illustrated in Figure 12.5. Assume the soil has not been disturbed or amended with plant residues for some time. Initially, little or no readily decomposable materials are present. Competition for food is severe and microbial activity is relatively low, as reflected in the low **soil respiration** rate or level of CO_2 emission from the soil. The supply of soil carbon is steadily being depleted. Small populations of microorganisms survive by slowly digesting the very resistant, stable soil organic matter. Soil ecologists consider these microorganisms to exhibit a K-strategy for survival, so named because they have developed enzymes with high affinity constants (*K*) for specific types of resistant substrates. The **K-strategists** have a competitive advantage when the soil is poor in easily digested organic materials. These organisms maintain a low but fairly constant population by carrying out specialized reactions.

Now suppose that deciduous trees in a forest begin to lose their leaves in fall or a farmer plows in residues of a harvested crop. The appearance of easily decomposable and often water-soluble compounds, such as sugars, starches, and amino acids, stimulates an almost immediate increase in metabolic activity among the soil microbes. Soon the slower-acting K-strategists are overtaken by rapidly multiplying populations of *opportunist* or *colonizing* organisms that have been awakened from their dormant state by the presence of new food supplies. These organisms are known as **r-strategists**, so named for their rapid rate (r) of growth and reproduction that allows them to take advantage of a sudden influx of food.

Microbial numbers and carbon dioxide evolution from microbial respiration both increase exponentially in response to the new food resource (upper panel in Figure 12.5). Soon microbial activity is at peak intensity, energy is being rapidly liberated, and carbon dioxide is being formed in large quantities. As organisms multiply, they increase the **microbial biomass** and also synthesize new exocellular organic compounds. The microbial biomass at this point

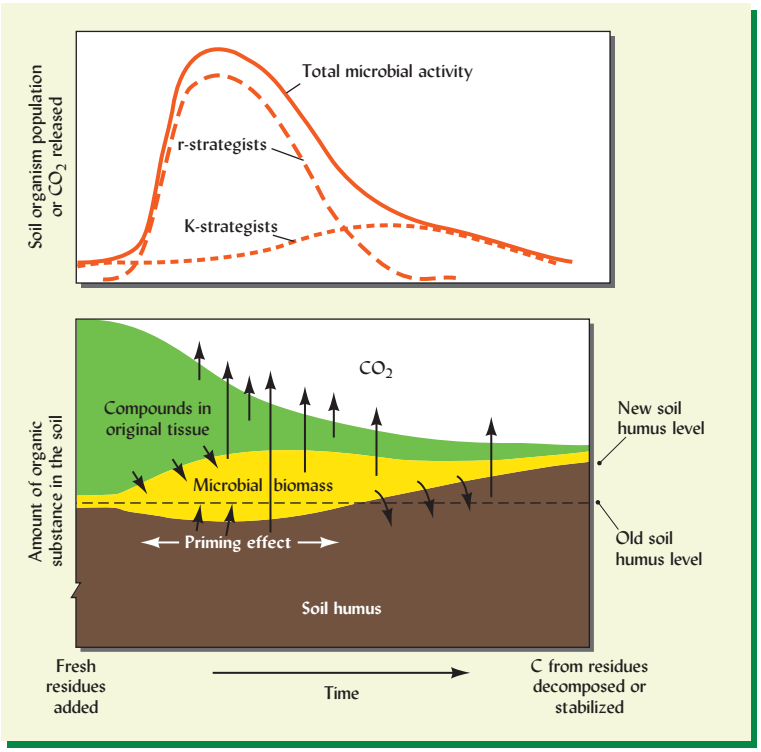

Figure 12.5 *Schematic of the general changes occurring when fresh plant residues are added to a soil. The arrows indicate transfers of carbon among compartments. The upper panel shows the relative growth or activity of r-strategist (opportunist), K-strategist (more specialized) microorganisms, and the sum of these two groups. The time required for the process will depend on the nature of the residues and the soil. Most of the carbon released during the initial rapid breakdown of the residues is converted to carbon dioxide, but smaller amounts of carbon are converted into microbial biomass (and synthesis products) and, eventually, into the various forms of non-living organic materials known as humus. The peak level of microbial activity appears to accelerate the decay of the original humus, a phenomenon known as the priming effect. However, the humus level is increased by the end of the process. Where vegetation, environment, and management remain stable for a long time, the soil humus content will reach an equilibrium level at which the carbon added to the humus pool through the decomposition of plant residues is balanced by carbon lost through the decomposition of existing soil humus.* (Diagram courtesy of Ray R. Weil)

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may account for as much as one-sixth of the organic matter in the soil. The intense microbial activity may even stimulate the breakdown of some of the more protected soil organic matter, a phenomenon known as the **priming effect**.

With all this frenetic microbial activity, the supply of easily accessible and decomposable compounds becomes depleted. In addition, microbial-feeding protozoa and nematodes move in to gorge on the masses of bacteria and fungi. While the specialized K-strategists continue their slow work, degrading cellulose and lignin, r-strategists begin to die of starvation and predation. As microbial populations plummet, the dead cells provide a readily digestible food source for the survivors, which continue to evolve carbon dioxide and water. The decomposition of the dead microbial cells and nematode excretions are also associated with the **mineralization** or release of simple inorganic products, such as nitrates and sulfates. As food supplies are further reduced, microbial activity continues to decline, and the general-purpose r-strategists again sink back into comparative quiescence and most of the microbial feeders die off (and decompose) or move on. A small amount of the original residue material persists, mainly as tiny particles that have become **physically protected** from decay by lodging inside soil pores too tight to allow access by most organisms. Some of the remaining carbon compounds, including microbial cell wall materials and plant biomolecules have been **chemically protected** from rapid decay by binding tightly with the surfaces of mineral particles. This remaining organic matter, referred to as humus, is largely a dark-colored, heterogeneous, mostly colloidal-sized mixture of, bits of plant and microbial tissues, modified lignin and other plant compounds. It is considered stabilized organic matter because it is much less water soluble than the sugars and starches that were the first to be digested by the microbial community and because its association with the mineral fraction of the soil makes it less susceptible to enzymatic attack. Thus, a small percentage of the carbon originally present in the added residues has been retained, increasing slightly the pool of relatively stable soil organic matter (humus). If undisturbed for many years, an ecosystem will come into equilibrium such that the small increase in retained C will likely be offset during each annual cycle by slow, steady K-strategy decomposition, resulting in little net change in the level of soil organic matter from year to year.

Production of Simple Inorganic Products

As proteins are attacked by microbes, the long chains of amino acids are broken, and individual amino acids appear in the soil solution along with dissolved CO_2. The amide (—R—NH_2) and sulfide (—R—S) groups of the amino acids, in turn, are broken off to produce, first, ammonium (NH_4^+) and sulfide (S^{2-}) compounds and, finally, nitrates (NO_3^-) and sulfates (SO_4^{2-}). Similar decomposition of other organic compounds releases these and other inorganic (mineral) nutrient ions. The process that releases elements from organic compounds to produce inorganic (mineral) forms is known as **mineralization**; it is of major importance in supplying nitrogen, sulfur, phosphorus, and other essential elements for plant growth.

Decomposition in Anaerobic Soils

Oxygen supplies may become depleted when soil pores filled with water prevent the diffusion of O_2 into the soil from the atmosphere. Without sufficient oxygen present, aerobic organisms cannot function, so anaerobic or facultative organisms become dominant. Wet, anaerobic soils tend to accumulate large amounts of partially decomposed organic matter for two reasons: First, under low-oxygen or anaerobic conditions, decomposition takes place much more slowly than when oxygen is plentiful. Second, certain products of anaerobic metabolism are toxic to many microbes, acting as a preservative for organic matter.

The products of anaerobic decomposition include a wide variety of partially oxidized organic compounds, such as organic acids, alcohols, and methane gas. Anaerobic decomposition releases relatively little energy for the organisms involved; therefore, the end products still contain much energy. (For this reason, alcohol and methane, which are produced by anaerobic decomposition, can serve as fuel.) Some of the products of anaerobic decomposition are of

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concern because they produce foul odors or inhibit plant growth. The methane gas produced in wet soils is greenhouse gas and a major contributor to climate change (Section 12.9). The following reactions are typical of those carried out in wet soils by various **methanogenic bacteria** and **archaea**:

$$\underset{\text{Propionate}}{4C_2H_5COOH} + 2H_2O \xrightarrow{\text{Bacteria}} \underset{\text{Acetate}}{4CH_3COOH} + \underset{\text{Carbon}}{CO_2\uparrow} + \underset{\text{Methane}}{3CH_4\uparrow} \tag{12.2}$$

$$CH_3COOH \xrightarrow{\text{Bacteria}} CO_2\uparrow + CH_4\uparrow \tag{12.3}$$

$$CO_2 + 4H_2 \xrightarrow{\text{Bacteria}} 2H_2O + CH_4\uparrow \tag{12.4}$$

12.3 FACTORS CONTROLLING RATES OF RESIDUE DECOMPOSITION AND MINERALIZATION[2]

It may take from days to years for the just described processes of decomposition and mineralization to run their course, depending mainly on two broad factors: (1) the environmental conditions in the soil, and (2) the quality of the added residues as a food source for soil organisms.

The environmental conditions conducive to rapid decomposition and mineralization (see also Sections 11.11 and 12.8) include sufficient soil moisture but with good aeration (about 60% of the soil pore space filled with water), warm temperatures (up to about 35°C), and a near-neutral pH. Ironically, periodic stresses such as episodes of severe drying actually accelerate overall mineralization due to the dramatic burst of microbial activity that occurs each time the soil re-wets (e.g., Figure 13.7). These conditions were discussed in Section 11.11 in relation to microbial activity and will be considered again in Section 12.8 as they affect the levels of organic matter accumulating in soils. Here we will focus on factors that determine the quality of the residues as a food resource for microbes, including the physical condition of the residues, their C/N ratio, and their content of lignins and polyphenols.

Physical Factors Influencing Residue Quality

The location of residues in or on the soil is a physical factor that has a critical impact on decomposition rates. Surface placement of plant residues, as in forest litter or conservation tillage mulch, usually results in slower, more variable rates of decomposition than where similar residues are incorporated into the soil by root deposition, faunal action, or tillage. Surface residues are subject to rapid drying, as well as extremes of temperature. Nutrient elements mineralized from surface-applied residues are also more susceptible to loss in runoff or by volatilization than are those from incorporated residues. Surface residues are physically out of reach for most soil organisms, so fungal mycelia and larger fauna such as earthworms have a special role to play. Fungal mycelia have been shown to grow up from the soil to invade surface litter (see Figure 11.29). If the surface litter is low in nitrogen, fungi may even transfer nitrogen from the soil through their hyphae to lower the C/N ratio of the litter (see following). Compared to surface residue, incorporated residues experience much more constant moisture and temperature and are in intimate contact with soil moisture and soil organisms. The incorporated residues therefore, decompose more quickly and uniformly, and may lose nutrients more easily by leaching.

Residue particle size is another important physical factor—the smaller the particles, the more rapid the decomposition. Small particle size may result from the nature of the residues

[2]For an excellent collection of papers dealing with litter decomposition in soils, see Cadisch and Giller (1997). Experimental values and mechanistic modeling of the influence of soil moisture, and residue physical placement and quality can be found in Coppens et al. (2007).

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(e.g., twigs versus branches), from mechanical treatment (grinding, chopping, tillage, etc.), or from the chewing action of soil fauna. Shredding residues into smaller particles physically exposes more surface area to decomposition and also breaks up lignacious cell walls and waxy outer coatings on leaves exposing more readily digested tissues and cell contents. In addition, some organic materials, including tiny bits of plant tissue lodged in aggregates, exhibit hydrophobicity (water repellency), making them slow to wet and resistant to attack by water-soluble microbial enzymes.

Plant root exudates and dead roots, which can account for 20–50% of total plant residues (see Section 11.7), are obviously located in the soil, often very deep in the profile. Root residues generally decompose more slowly than aboveground residues, even those that have been incorporated into the soil. As such, root residues present a special case both in terms of physical placement and chemical composition (see next).

Carbon/Nitrogen Ratio of Organic Materials and Soils

The carbon content of typical plant dry matter is about 40–45% (see Figure 12.4). The nitrogen content of plant residues is much lower but more variable (ranging from <1 to >6%). The ratio of carbon to nitrogen (C/N) in organic residues applied to soils is important for two reasons: (1) intense competition among microorganisms for available soil nitrogen occurs when residues having a high C/N ratio are added to soils, and (2) the residue C/N ratio helps determine the rate of decay and the rate at which nitrogen is made available to plants.

C/N Ratio in Plants and Microbes. The C/N ratio in plant residues ranges from between 8:1 to 30:1 in legumes and young green leaves to higher than 500:1 in some kinds of sawdust and charred materials (Table 12.2). Generally, as plants mature, the proportion of protein in their tissues declines, while the proportion of lignin and cellulose, and the C/N ratio, increase. As can be seen from the decay curves in Figure 12.6, these differences in composition have pronounced effects on the rate of decay when plant residues are added to the soil. Such decay curves typically show a steep slope initially and lower slope during later phases. This shape suggests that different plant residues have differing proportions of their C distributed between two generalized pools: (1) a metabolic pool with high rates of initial decomposition representing mainly cytoplast contents such as starch, sugars, and proteins; and (2) a structural pool with slower initial decomposition that represents mainly cell wall constituents such as lignin and cellulose. The C/N ratio of the metabolic pool is generally < 25:1 while that of the structural pool is usually > 100:1.

In the bodies and cells of microorganisms, the C/N ratio is not only less variable than in plant tissues, but also much lower, ordinarily falling between 5:1 and 10:1. Among microorganisms, bacteria are generally richer in protein than fungi and, consequently, have a lower C/N ratio.

C/N Ratio in Soils. The C/N ratio in the organic matter of arable (cultivated) surface (Ap) horizons commonly ranges from 8:1 to 15:1, the median being near 12:1. The ratio is generally lower for subsoils than for surface layers in a soil profile. In a given climatic region, little variation occurs in the C/N ratio for similarly managed soils. For instance, in calcium-rich soils of semiarid grasslands (e.g., Mollisols and tropical Alfisols), the C/N ratio is relatively narrow. In more severely leached and acidic A horizons in humid regions, the C/N ratio is relatively wide; C/N ratios greater 20:1 are not uncommon. Forest O horizons commonly have C/N ratios of 30–40. When such soils are brought under cultivation and limed to increase their pH and calcium content, the enhanced decomposition tends to lower the C/N ratio to near 12:1.

Influence of Carbon/Nitrogen Ratio on Residue Decomposition

Soil microbes, like other organisms, require a balance of nutrients from which to build their cells and extract energy. The majority of soil organisms metabolize carbonaceous materials

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Table 12.2
TYPICAL CARBON AND NITROGEN CONTENTS AND C/N RATIOS OF SOME ORGANIC MATERIALS COMMONLY ASSOCIATED WITH SOILS

Organic material	% C	% N	C/N
Spruce sawdust	50	0.05	600
Hardwood sawdust	46	0.1	400
Newspaper	39	0.3	120
Biochar from corn cobs	77	0.85	91
Wheat straw	38	0.5	80
Beech tree leaves	51	7.8	65
Corn stover	45	0.75	60
Sugarcane trash	40	0.8	50
Biochar from corn stover	57	1.4	40
Rye cover crop, anthesis	40	1.1	37
Maple leaf litter	48	1.4	34
Rye cover crop, vegetative stage	40	1.5	26
Mature alfalfa hay	40	1.8	25
Rotted barnyard manure	41	2.1	20
Bluegrass from fertilized lawn	42	2.2	20
Broccoli residues	35	1.9	18
Finished household compost	30	2.0	15
Young alfalfa hay	40	3.0	13
Hairy vetch cover crop	40	3.5	11
Class A municipal biosolids (sewage sludge)	35	6.1	6
Soil microorganisms			
Bacteria	50	10.0	5
Actinomycetes, nematodes	50	8.5	6
Fungi	50	5.0	10
Soil organic matter			
Spodosol O horizon	50	0.5	90
Average forest O horizons	50	1.3	45
Average forest A horizons	50	2.8	20
Tropical evergreen litter	50	2.0	25
Mollisol Ap horizon	56	4.9	11
Average B horizon	46	5.1	9

both in order to obtain carbon for building essential organic compounds and to obtain energy for life processes. However, no creature can multiply and grow on carbon alone. Organisms must also obtain sufficient nitrogen to synthesize nitrogen-containing cellular components, such as amino acids, enzymes, and DNA.

On the average, soil microbes must incorporate into their cells about eight parts of carbon for every one part of nitrogen (i.e., assuming the microbes have an average C/N ratio of 8:1). Because only about one-third of the carbon metabolized by microbes is incorporated into their cells (the remainder is respired and lost as CO_2), the microbes need to find about 1 g of N for every 24 g of C in their "food."

This requirement results in two extremely important practical consequences. First, if the C/N ratio of organic material added to soil exceeds about 25:1, the soil microbes will have to scavenge the soil solution to obtain enough nitrogen. Thus, the incorporation of

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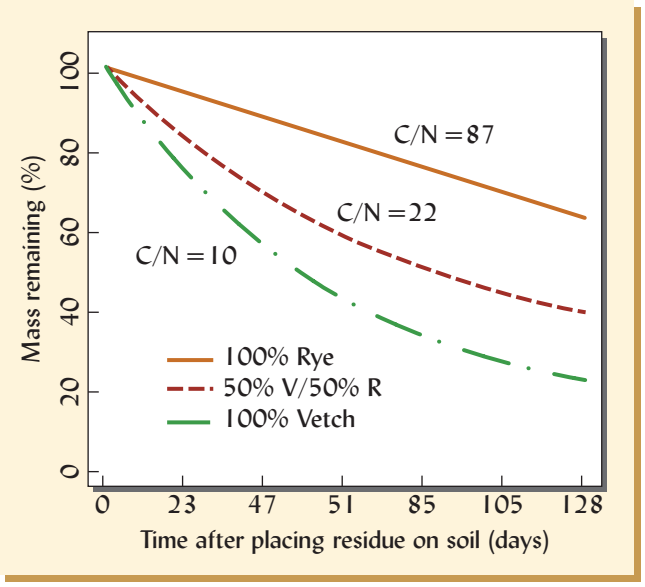

Figure 12.6 *Rates of decomposition residues from a legume (hairy vetch) and a grass (cereal rye) cover crop and an approximately 50:50 mixture of the two. The lower the initial C/N ratio of the residues, the more rapid the initial decomposition process (shown as the decline of the mass remaining). By 120 days the initial supply of readily digestible carbon was used up and the decomposition rates (slopes) all became similar. The cover crops were grown from late fall, over the winter to spring planting time, then killed by a machine that rolls them down and crimps the stems. The residues were left as a mulch on the soil surface (the measurements were made by periodically retrieving mesh litter bags that had been filled with known quantities of the cover crop residues and pinned to the soil surface). Corn was planted into this mulch without tillage.* [Based on data in from Poffenbarger et al. (2015)]

high C/N residues will deplete the soil's supply of soluble nitrogen, causing plants to suffer from nitrogen deficiency. Second, the decay of organic materials can be delayed if sufficient nitrogen to support microbial growth is neither present in the material undergoing decomposition nor available in the soil solution. These concepts are illustrated by the example in Figure 12.7.

Examples of Inorganic Nitrogen Release During Decay

The practical significance of the C/N ratio becomes apparent if we compare the changes that take place in the soil when residues of either high or low C/N ratio are added (Figure 12.8). Consider a soil with a moderate level of soluble nitrogen (mostly nitrates). General-purpose decay organisms are at a low level of activity in this soil, as evidenced by low carbon dioxide production. If no nitrogen were lost or taken up by plants, the level of nitrates would very slowly increase as the native soil organic matter decays.

Low Nitrogen Material. Now consider what happens when a large quantity of readily decomposable organic material is added to this soil. If this material has a C/N ratio greater than 25, changes will occur according to the pattern shown in Figure 12.8 (*top*). In the example shown, the initial C/N ratio of the residues is about 55, typical for many kinds of leaf litter and also for cornstalks. As soon as the residues contact the soil, the microbial community responds to the new food supply (see Section 12.2). Heterotrophic r-strategist microorganisms become active, multiply rapidly, and yield carbon dioxide in large quantities. Because of the microbial demand for nitrogen, little or no mineral nitrogen (NH_4^+ or NO_3^-) is available to higher plants during this period.

Nitrate Depression. This condition, often called the **nitrate depression period**, persists until the activities of the decay organisms gradually subside due to lack of easily oxidizable carbon. As their numbers decrease, carbon dioxide formation drops off, and nitrogen demand by microbes becomes less acute. As decay proceeds, the C/N ratio of the remaining plant material decreases because carbon is being lost (by respiration) and nitrogen is being conserved (by incorporation into microbial cells). Generally, one can expect mineral nitrogen to begin to be released when the C/N ratio of the remaining material drops below about 20. Then, nitrates appear again in quantity, and the original conditions prevail, except that the soil is somewhat richer in both nitrogen and humus.

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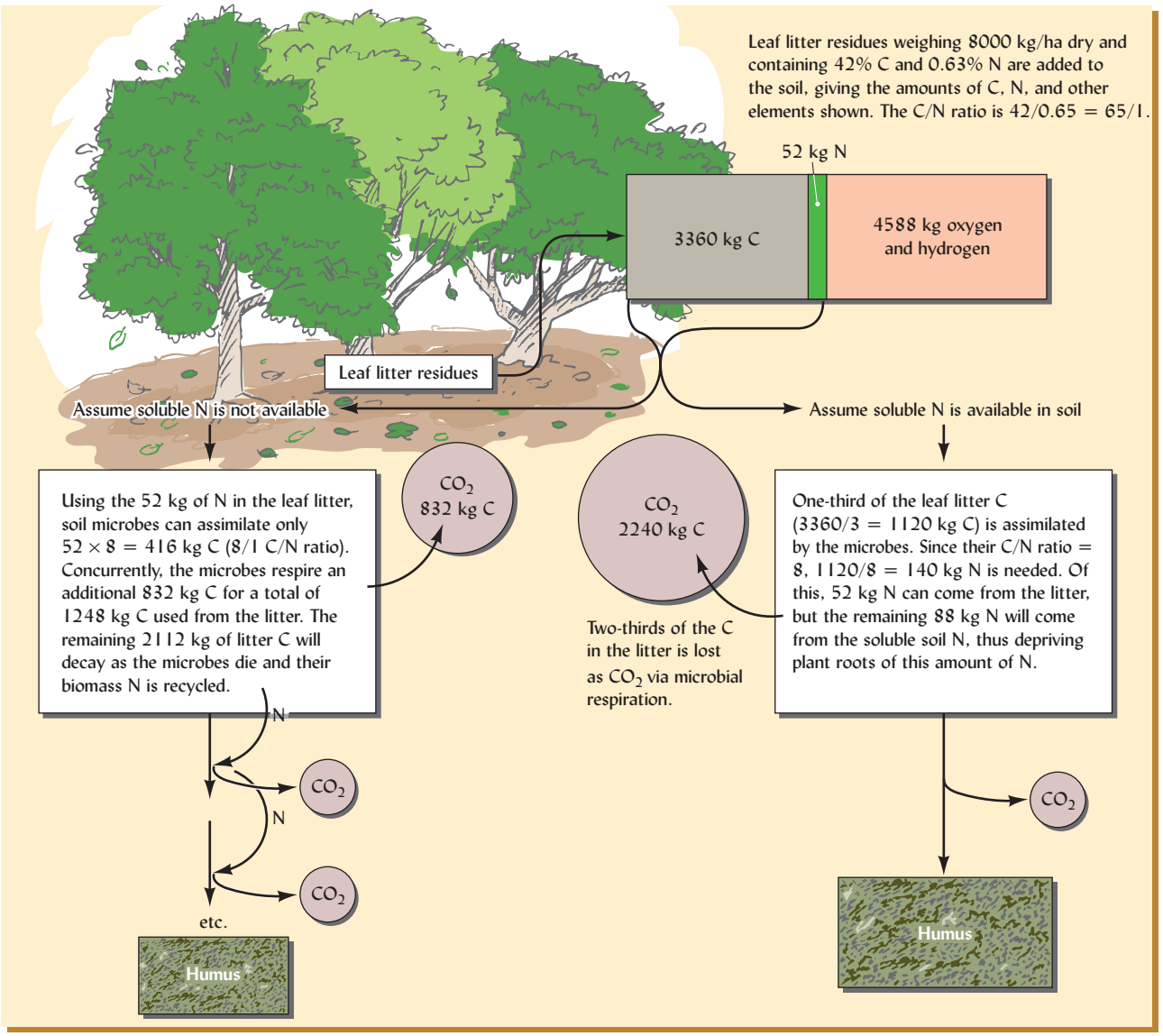

Figure 12.7 *A simplified, quantitative example of plant residue decay illustrating the fates of carbon and nitrogen and the consequences for decomposition and soil nitrogen availability. Note that if the supply of nitrogen is low, the decomposition process is slowed, and eventually less carbon remains as stabilized humus.* (Diagram courtesy of Ray R. Weil)

The nitrate depression period may last for a few days, a few weeks, or even several months. A longer, more severe period of nitrate depression is typical when added residues are easily decomposed and have a higher C/N ratio and when a larger quantity of residues is added. To avoid producing seedlings that are stunted, chlorotic, and nitrogen-starved, planting should be delayed until after the nitrate depression period or additional sources of nitrogen can be applied to satisfy the nutritional requirements of both the microbes and the plants.

High Nitrogen Material. The effects on soil nitrate level will be quite different if the residues added have a C/N ratio lower than 20, as in the case represented by Figure 12.8 (*bottom*).

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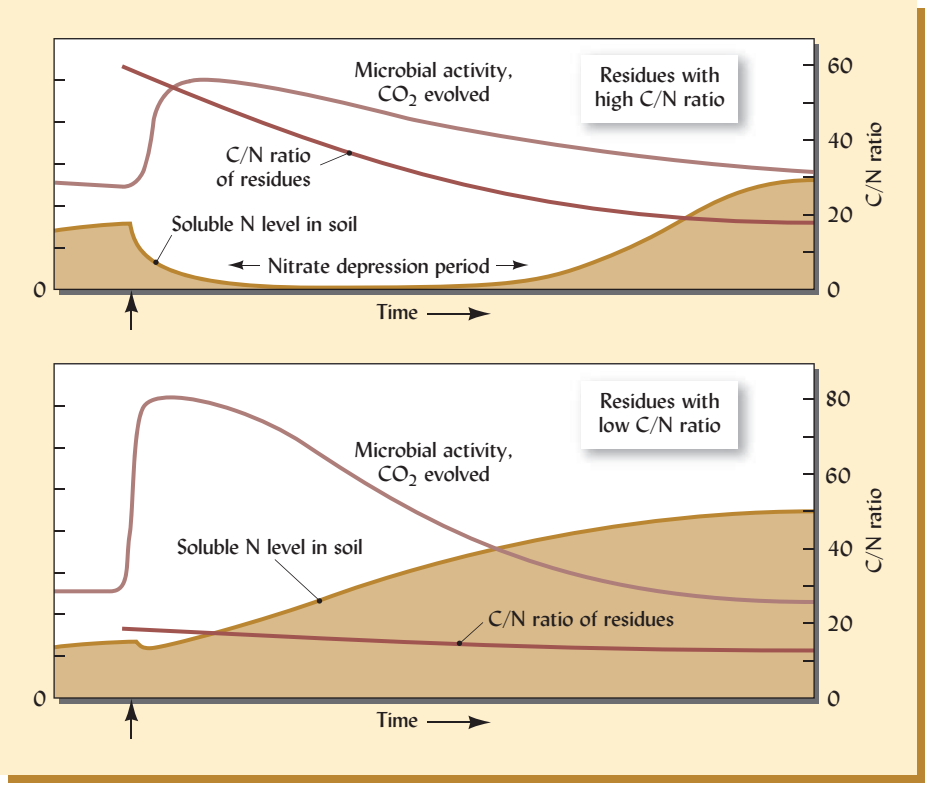

Figure 12.8 *Changes in microbial activity, in soluble nitrogen level, and in residual C/N ratio following the addition of either high* (top) *or low* (bottom) *C/N ratio organic materials. Where the C/N ratio of added residues is above 25, microbes digesting the residues must supplement the nitrogen contained in the residues with soluble nitrogen from the soil. During the resulting nitrate depression period, competition between higher plants and microbes would be severe enough to cause nitrogen deficiency in the plants. Note that in both cases soluble N in the soil ultimately increases from its original level once the decomposition process has run its course. The trends shown are for soils without growing plants, which, if present, would continually remove a portion of the soluble nitrogen as soon as it is released.* (Diagram courtesy of R. Weil)

With organic materials of low C/N ratio, more than enough nitrogen is present to meet the needs of the decomposing organisms. Therefore, soon after decomposition begins, some of the nitrogen from organic compounds is released into the soil solution, augmenting the level of soluble nitrogen available for plant uptake. Generally, nitrogen-rich materials decompose quite rapidly, resulting in a period of intense microbial growth and activity, but no nitrate depression period.

Influence of Soil Ecology

In nature, the process of nitrogen mineralization involves the entire food web (see Section 11.2), not just the saprophytic bacteria and fungi. For example, when organic residues are added to soil, bacteria and fungi grow rapidly on this food source, producing a large biomass of bacterial and fungal cells that contain much of the nitrogen originally in the residues. Until the microbial biomass begins to die off, this nitrogen is immobilized and not available to plants. However, a healthy soil ecosystem is likely to contain certain nematodes, protozoa, and earthworms that feed on bacteria and fungi. As these animals feed, they respire most of the carbon in the microbial cells, using only a small fraction to grow on (or produce eggs). Since the C/N ratio of these animals is not too different from that of their microbial food, and since most of the carbon is converted to CO_2 by respiration, the animals soon ingest more nitrogen than they can use. They then excrete the excess nitrogen, mainly as NH_4^+, into the soil solution as plant-available mineral nitrogen. The microbial feeding activity of soil animals may increase the rate of nitrogen mineralization dramatically as shown in Figure 12.9 for bacterial-feeding nematodes and fungal-feeding collembola. Bacterial-feeding nematodes seem to have less effect on nitrogen mineralization when the C/N ratio of residues is very wide, because nitrogen excreted by the nematodes under these conditions would be quickly re-immobilized by bacteria that have plenty of carbon, but little nitrogen, to grow on. In any case, soil management that favors a complex food web (Section 11.14) with many trophic levels can be expected to enhance the cycling and efficient use of nitrogen (and of other nutrients).

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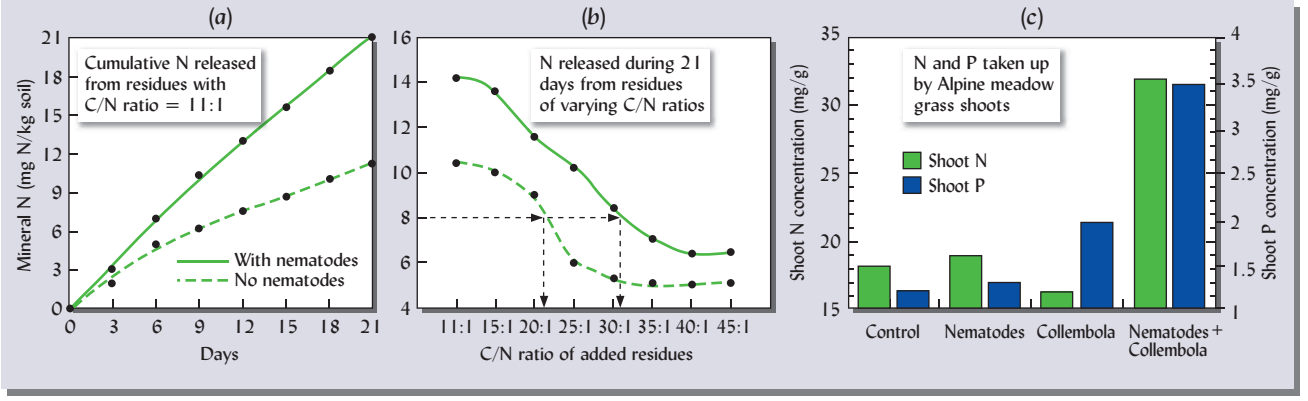

Figure 12.9 *Microbial-feeding fauna enhance the release of plant-available mineral nutrients from organic residues. (a and b) Columns of sandy soil with well established bacterial communities were amended the soil with ground alfalfa tissue (low C/N) and cellulose (high C/N) in varying proportions to give the indicated C/N ratios. Some of the soil columns were inoculated with bacteria-feeding nematodes (Cephalobus persegnis) and some were free of nematodes.* (a) *By feeding on the bacteria, the nematodes nearly doubled the amount of mineral N released from the added residues over a 21-day period. Without nematodes, much of the N was tied up in the bacterial biomass, but when the nematodes ate the bacteria, they excreted the excess N into the soil solution as* NH_4^+. (b) *Nematodes influenced the release of mineral N from residues with different C/N ratios. Enhanced mineralization in the presence of bacteria-feeding nematodes suggests that a level of mineral N satisfactory for plant growth (say 8 mg/kg) could be maintained with residues of relatively high C/N ratio (about 32:1), but that without these nematodes, a more N-rich type of residue (C/N ratio about 22:1) would be required. In an alpine meadow soil* (c) *bacteria-feeding nematodes worked synergistically with mainly fungal-feeding collembola to increase the amount of both N and P released and subsequently taken up by grass plants.* [Graphs (a) and (b) drawn from data in Ferris et al. (1998); graph (c) drawn from data in Bardgett and Chan (1999)]

Influence of Lignin and Polyphenol Content

The lignin contents of plant litter range from less than 2% to more than 50%. Those materials with high lignin content usually decompose very slowly. Polyphenol compounds found in plant litter may also inhibit decomposition. These phenolics are often water-soluble and may be present in concentrations as high as 5–10% of the dry weight. By forming highly resistant complexes with proteins during residue decomposition, these phenolics can dramatically slow the rates of both nitrogen mineralization and carbon oxidation.

Litter Quality. Because they support relatively low levels of microbial activity and biomass, residues high in phenols and/or lignin are considered to be *poor quality resources* for the soil organisms that cycle carbon and nutrients. The production of such slow-to-decompose residues by certain forest plants may help explain the accumulation of extremely high levels of stable organic nitrogen and carbon in the soils of mature boreal forests.

The lignin and phenol contents also influence the decomposition and release of nitrogen from **green manures**—plant residues used to enrich agricultural soils (Table 12.3). For example, in the leaves of certain legume trees, the C/N ratio is quite low, but the phenol content is quite high, so that when these leaves are added to soil, nitrogen is released only slowly—often too slowly to keep up with the needs of a growing crop. Similarly, residues with a lignin content of more than 20–25% will decompose too slowly to be effective as green manure for rapidly growing annual crops. However, for perennial crops, or forests, the slow release of nitrogen from such residues may be advantageous in the long run, as the nitrogen may be less subject to losses. By the same token, the slow decomposition of phenol- or lignin-rich materials means that even if their C/N ratio is very high, the nitrate depression will not be pronounced.

Figure 12.10 illustrates the combined effects of C/N ratio and lignin or phenol content on the balance between immobilization and mineralization of nitrogen during plant residue decomposition.

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Table 12.3
LITTER QUALITY IN RELATION TO THE LIGNIN CONTENT, POLYPHENOL CONTENT, AND C/N RATIO AND RATE OF DECAY OF SEVERAL TYPES OF MATERIALS AS MEASURED AT TROPICAL AND TEMPERATE SITES
Low values of C/N, lignin, and polyphenols all contribute to high litter quality and speed of decomposition. Crop residues tend to be low in lignin and polyphenol. For similar materials, decay is much faster (k values are larger) in the tropical climate. The inhibitory effect of polyphenol content can be seen by comparing Gliricidia to Leucaena. The effect of climate and C/N ratio (related to N fertilization) can be seen by comparing the two maize residues.

Plant species	Plant parts	Lignin, %	Polyphenols, %	Total N, %	C/N	Decay constant,[a] k, per week	Litter quality
Measured under humid tropical conditions in Nigeria							
Gliricidia sepium	Prunings	12	1.6	3.5	13	0.255	High
Leucaena leucocephala	Prunings	13	5.0	3.5	13	0.166	Medium-high
Oryza sativa (Rice)	Residues	5	0.6	1.0	42	0.124	Medium
Zea mays (Corn)	Residues	7	0.6	1.1	43	0.119	Medium
Dactyladenia barteri	Prunings	47	4.1	1.6	28	0.011	Low
Measured under temperate subhumid conditions in Missouri, USA							
Poa trivialis (Bluegrass)	Hay	8	0.2	2.2	19	0.027	Medium-high
Glycine max (Soybean)	Residues	9	0.2	2.2	20	0.020	Medium-high
Zea mays (Corn)	Residues	7	0.3	1.5	28	0.014	Medium
Acer saccharinum (Silver maple)	Fallen leaves	11	4.8	1.4	34	0.013	Medium
Carya illinoinensis (Pecan)	Fallen leaves	25	2.1	1.1	42	0.012	Medium

[a]As each type of residue decomposed, researchers periodically determined the proportion Y of the original residue dry matter remaining. The long-term decomposition rate *k* was determined from the equation $Y = e^{-kt}$ in which e is the base of natural logarithms (2.72), and *t* is time in weeks. Therefore, the larger the decomposition constant *k*, the faster the decomposition.

Data selected from Mungai and Motavalli (2006) and Tian et al. (1992, 1995).

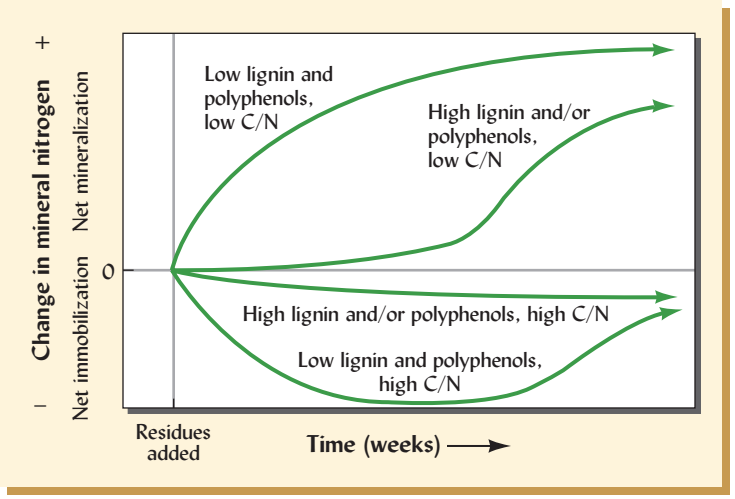

Figure 12.10 *Temporal patterns of nitrogen release from organic residues differing in quality based on their C/N ratios and contents of lignin and polyphenols. Lignin contents greater than 20%, polyphenol contents greater than 3%, and C/N ratios greater than 30 would all be considered high in the context of this diagram, the combination of these properties characterizing litter of poor quality—that is, litter that has a limited potential for rapid microbial decomposition and mineralization of plant nutrients.* (Diagram courtesy of Ray R. Weil)

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12.4 GENESIS AND NATURE OF SOIL ORGANIC MATTER AND HUMUS[3]

In this textbook, we use the general term **soil organic matter** to refer to the entire organic portion of the soil (Figure 12.11), recognizing that soil organic matter is not a single substance but a complex mixture of substances that exist in association with other soil components. Although surface residues (litter) are not universally considered to be part of the soil organic matter, we include them (mainly in the detritus fraction) in this textbook because they comprise a major part of the O horizons in many soil profiles.

Since the element carbon (C) plays a prominent role in the chemical structure of all organic substances, it is not surprising that the term **soil organic carbon** (SOC) is also often used to refer to the C component of soil organic matter. This term is particularly appropriate for quantitative discussions of soil organic matter because most methods of determining soil organic matter actually measure the C in the material and then use a conversion factor to estimate the organic matter. Since soil organic matter commonly contains about half carbon by weight (50% C), it is usually appropriate to estimate soil organic matter as two times the organic C (SOM = 2 × SOC).[4] However, the C content of soil organic matter does vary, so caution must be used when comparing values reported as soil organic matter and soil organic carbon!

The term soil organic matter encompasses all the organic components of a soil: (1) living **biomass** (intact plant and animal tissues and microorganisms); (2) plant litter or residues—bits of dead roots and other plant residues in various stages of decay and of various sizes (although in practice, particles that do not pass 2-mm sieve openings are often excluded from consideration); (3) dissolved organic biomolecules ranging widely from plant amino acids to microbial enzymes; and (4) a complex mixture of biomolecule agglomerations on particle surfaces, tiny bits of no longer identifiable tissue occluded inside microaggregates, and bits of plant material that have been blackened (charred) by fire. As in Figure 12.11, we will refer to the various components in this fourth broad category of organic material as **soil humus** (pronounced *hew-muss)*, and those in the first three categories as the **labile carbon** pool (or group). The word labile (*liable to change; easily altered*) implies that the C-containing materials in this pool are subject to rapid oxidation by soil organisms over periods of months to years. In contrast, the carbon in the humus pool appears to be stabilized by various mechanisms that enable it to remain in the soil for relatively long periods (centuries or even millennia). Within each of the two pools, Figure 12.11 defines several organic matter fractions based on chemical and physical criteria. Organic matter is separated into labile and humus pools largely because of the degree to which their component compounds are physically protected from decay by the soil environment, especially by association with soil mineral particles and aggregates. Thus certain chemically similar organic matter fractions may appear to be labile when in a "free" or unprotected condition and appear to be part of the more stable humus pool when in a protected condition. We can summarize the concept of two organic matter pools with a business analogy: *the labile C largely serves as ready cash flow to pay the workers (feed the soil food web) while humus can be seen as the (carbon) capital of the system (accumulated organic matter), which builds important chemical and physical aspects of the soil.*

Microbial Transformations

Microbial decomposition of plant residue leads to carbon cycling, mineral nutrient release, and the formation and accumulation of various forms of soil organic matter. During this process, microbes carry out two primary types of reactions: the oxidation of carbon and the breakdown of complex molecules into simpler compounds.

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[3]Our understanding of the nature and genesis of soil humus has advanced greatly since the turn of the century, requiring that some long-accepted concepts be revised or abandoned, as explained in detail by Schmidt et al. (2011) and Lehmann and Kleber (2015).

[4]Traditionally SOM has been estimated as 1.72 × SOC, a conversion that assumes 58% C in the soil organic matter. Although certain materials, such as humic acids, found in soil extracts do contain that much C, and there is little basis for the general use of this value; most organic matter in soils contains about 50% C, so a conversion factor of 2 is recommended.

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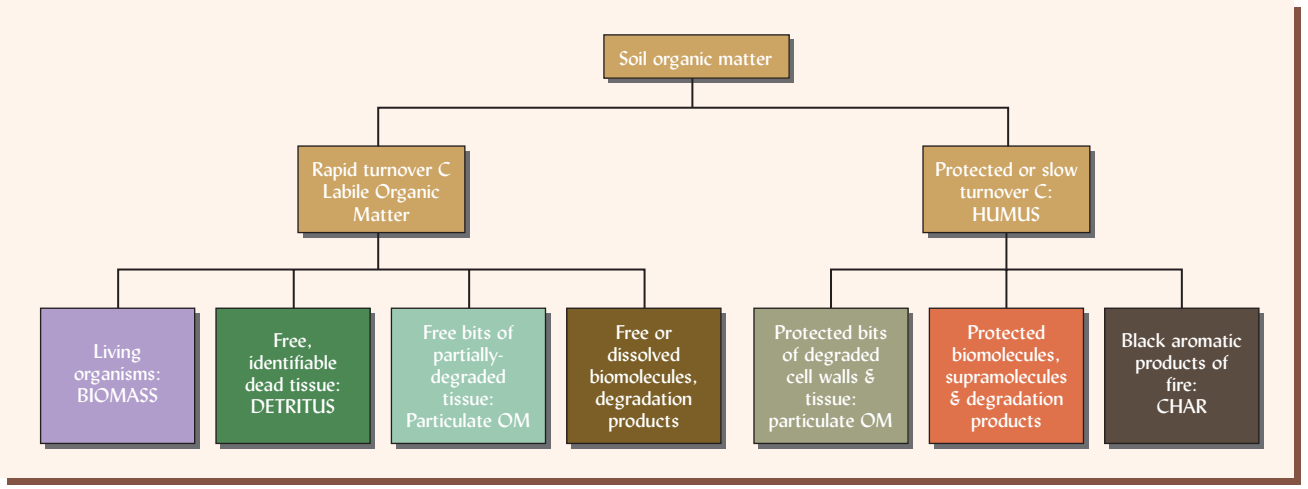

Figure 12.11 *Substances that comprise soil organic matter. The various components are classified first on the basis of their stability and availability to microbial turnover into two pools of carbon: (1) a rapidly oxidizing labile pool (taking months to years to disappear) and (2) a more stable, relatively slow-to-decompose pool (lasting for centuries or millennia) collectively referred to as humus. Within each of the two pools, several organic matter fractions are defined by chemical and physical criteria and the degree to which materials have been altered from the original living organisms. Organic matter behaves either as labile C or as humus partly because of differences in molecular structures, but more importantly because of the degree to which their component compounds are physically protected from decay by the soil environment, especially by association with soil mineral particles and aggregates. Thus, certain chemically similar components appear in both the labile (free or unprotected) and humus (protected) pools; examples include particulate organic matter (POM) and certain biomolecules (e.g., lipids, cellulose, glycoproteins and lignin). Char, a type of black carbon material produced by fire, is mostly (but not all) very slow to decompose and so is included with humus (far right compartment). This diagram is worth studying as reference will be made to these soil organic matter fractions throughout this and other chapters.* (Diagram courtesy of Ray R. Weil)

In the presence of O_2 oxidation reactions provide energy for microorganisms and create functional chemical groups like —COOH. These functional groups become charged when they dissociate (lose a H^+ ion), increasing the polarity of the molecule, which in turn increases its solubility and reactivity with mineral surfaces. The polarity of functional groups resulting from oxidation reactions therefore tends to transform many hydrophobic, nonpolar biomolecules such as lipids, lignin, and some proteins, into molecules that are more hydrophilic, more soluble, and more readily sorbed onto mineral surfaces.

The breakdown of large biopolymers into their component subunits—for example, cellulose into sugars or large lignin molecules into phenolic subunits—allows the soil microbes to then metabolize and oxidize the resulting simpler compounds. Using some of the carbon not lost as carbon dioxide in respiration, along with most of the nitrogen, sulfur, and phosphorus from these compounds, the microorganisms synthesize new cellular components and biomolecules. Some of these new microbial compounds and decomposition products, along with some modified plant compounds, will continue to be subject to microbial oxidation until completely transformed into CO_2, and mineral nutrients. Other compounds will interact with the soil environment in ways that slow or prevent their further decay.

The accumulation of organic matter in stabilized forms is controlled both by the particular soil environment and by the activity of the particular microbial community (Figure 12.12). The microbial biomass produces exocellular enzymes that break down both plant residues and microbial compounds from previous decomposition cycles, transforming components into dissolved organic carbon (DOC) compounds that the microbes can then utilize for energy. As these compounds are metabolized, most of the C is released as CO_2 while the other elements they contain (N, P, S, etc.) may be released into the soil solution. Not all soil organic matter is transformed rapidly to these end products.

Instead, some plant and microbial components become protected in various ways by the soil environment. For example, some bits of plant tissue and microbial cell walls—known

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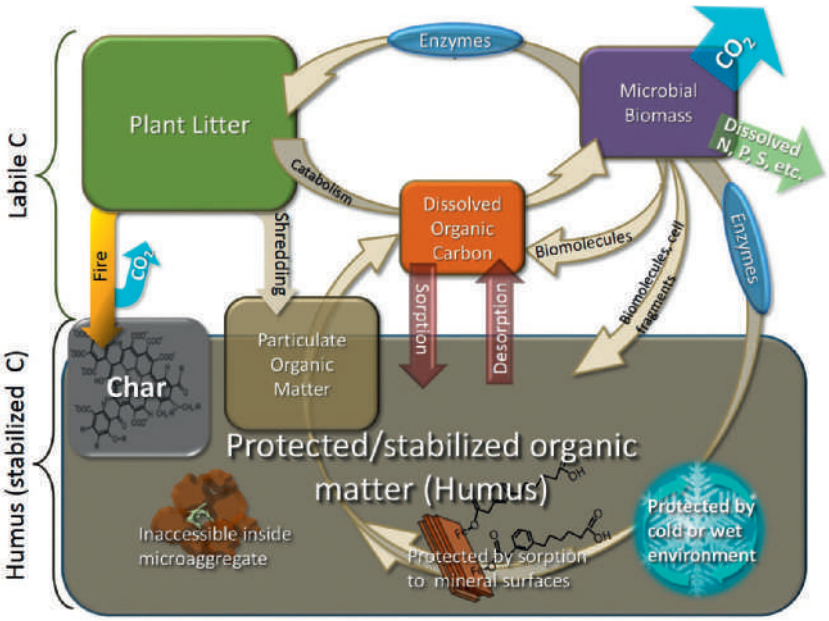

Figure 12.12 *Carbon cycling, mineral nutrient release and formation of soil organic matter. The microbial biomass* (upper right) *produces (mainly exocellular) enzymes that break down plant residues and microbial compounds from previous decomposition cycles, transforming components into dissolved organic C compounds. When these compounds are metabolized by microbes to obtain energy, most of their C is released as* CO_2 *while their other elements (N, P, S, etc.) may be released into the soil solution. The labile C (upper half of diagram) is subject to rapid metabolism, some components become stabilized (lower half of diagram). The soil environment and microbial activity control this stabilization and accumulation of organic matter. Bits of plant tissue and microbial cell walls (particulate organic matter) may become inaccessible to microbial attack as microaggregates form around them. Microbial oxidation creates zones of polarity in formerly hydrophobic biomolecules, allowing their C to become protected by bonding to mineral surfaces. Low temperatures or oxygen levels preserve plant and microbial compounds. Fires produce black carbon materials, which may resist enzymatic oxidation. Over time an individual C atom may move among any number of these pools.* (Diagram courtesy of Ray R. Weil)

as particulate organic matter (POM) become inaccessible to microbial attack when root soil microaggregates form around them. Microbial oxidation creates some zones of polarity in formerly hydrophobic plant and microbial biomolecules allowing them to become protected from further decay by bonding tightly in layers on mineral surfaces. In some soils, anaerobic (wet) or freezing cold conditions prevent complete oxidation and preserve plant and microbial compounds. In many soils, the charring process that occurs during fires produces black carbon materials that are quite immune to enzymatic attack and oxidation (see Box 12.2). By a combination of some or all of these mechanisms, a portion of the C entering the soil is preserved, allowing organic matter to accumulate over years and centuries.

Figure 12.13 provides a semiquantitative picture of these transformations. One year after plant residues are added to the soil, most of the carbon has returned to the atmosphere as CO_2, but one-fifth to one-third is likely to remain in the soil as live biomass (≈2–5%), nonliving labile C compounds (≈3–10%), and stabilized humus (≈10–30%). The proportion of C from root residues remaining after one year tends to be considerably higher than that remaining from incorporated leaf litter.

Examples of Biomolecules in Soil Organic Matter

Most of the soil organic matter is comprised of specific biomolecules, some of plant origin (albeit usually modified by microbial enzymes), while others are compounds synthesized by soil microbes as by-products or as part of their biomass. Included among these substances are bacterial polysaccharides, polymers that have sugarlike structures and a general formula of $C_n(H_2O)_m$, where n and m are variable. Another microbial compound found in large amounts in some soils is the fungal glycoprotein, glomalin. Polysaccharides and glomalin are especially important in enhancing soil aggregate stability (see Section 4.5). Also included among the microbially synthesized compounds are polyuronides. Some simpler compounds (such as low-molecular-weight organic acids and some protein-like materials) although not present in large quantities, may influence the availability of plant nutrients, such as nitrogen and iron, and may also directly affect plant growth.

Soil organic matter may also contain small amounts of materials known as ***humic substances***, which are highly complex, enormous polymers with many aromatic rings and molecular weights ranging from 2000 to >200,000. Unlike the components of humus

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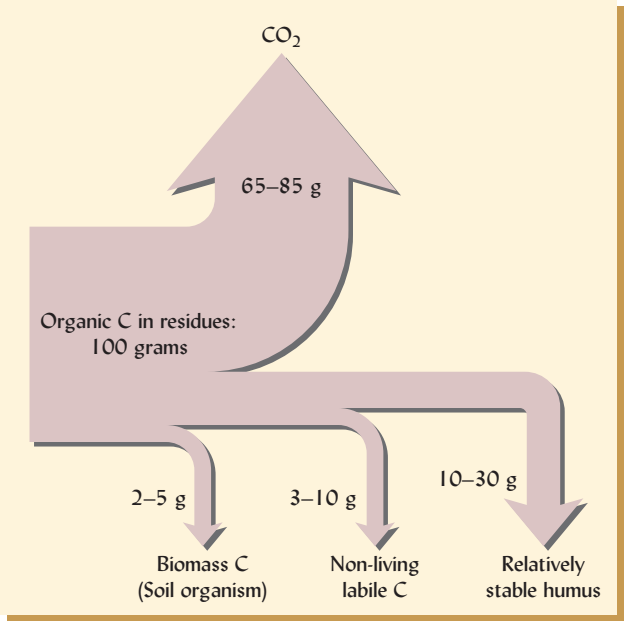

Figure 12.13 *Disposition of 100 g of organic carbon in residues one year after they were incorporated into the soil. More than two-thirds of the carbon has been oxidized to CO_2, and less than one-third remains in the soil—some in the cells of soil organisms, some in forms still readily accessible for further breakdown, but a larger component as relatively stabilized soil humus. The amount converted to CO_2 is generally greater for aboveground residues (litter) than for belowground (root) residues.* (Estimates from many sources)

discussed so far, these macromolecules are poorly characterized and not recognizable as biomolecules of either plant or microbial origin. They occur in certain natural waters, carbonaceous sediments, and in certain laboratory extracts made from soils and mined fossil carbon such as peat and lignite (soft coal). However, evidence now suggests that, despite their name, they are not the major components of soil humus that they have long been thought to be (see Box 12.3).

Colloid Characteristics of Humus

The nature and functional group chemistry of colloidal humus was described in Section 8.4. Because of the many types of chemical groups that, among them, absorb nearly all wavelengths of visible light, humus imparts a black color to soil as is most characteristic of O, A, and Bh horizons (see Figures 3.3, 3.16, 3.29). Humus colloids include tiny particles of char as well as multiple layers of organic compounds with varying degrees of polarity sorbed to clay surfaces. These materials exhibit very high levels of surface area and negative charge—similar per unit volume to those of high-activity clay, but much greater than clay when compared per unit mass. Depending on the pH, the cation exchange capacity of humus may range from about 150 to as high as 500 $cmol_c$/kg (about 40–120 $cmol_c$/L). The water-holding capacity of humus on a mass basis (but not on a volume basis) is four to five times that of the silicate clays. Humus promotes aggregate formation and stability, and, in turn, the aggregate structures help protect the humus from decay.

Stability of Humus

Protection of at least some C from microbial respiration enables soils to accumulate increasing amounts of organic matter over years and centuries (Section 12.8). Studies using the radioactive carbon isotope ^{14}C have shown that some organic C incorporated into plant tissue by photosynthesis thousands of years ago is still present in certain soils. Thus at least some C atoms in soils have escaped microbial respiration to CO_2, although they may have undergone many transformations. In fact, the date given by ^{14}C analysis tells us when the C was first fixed by photosynthesis, nothing more. For example, a ^{14}C date of 800 years may mean the C became part of a tree 800 years ago, then was in a twig in the litter layer for 20 years, then in a fungal hyphae for 2 years, then in an aggregate as a bit of fungal cell wall for 500 years, then something else, etc. It would be a misinterpretation to think the date means the specific carbon compound has remained in the soil unchanged for 800 years.

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BOX 12.2

CHAR: IS BLACK THE NEW GOLD?[a]

During wildfires 1–3% of the potential fuel is charred (blackened) rather than burned. The char is left in and on the soil (Figure 12.14). This black carbon (think of charcoal) is a product of **pyrolysis**—the smoldering or charring that takes place when organic material is heated to 280–500°C under low oxygen conditions. This contrasts with complete combustion that produces CO_2 and whitish mineral ash under high oxygen conditions. Since fires occur in most ecosystems, char is present in most soils. In most forests 5–10% of the soil organic carbon may be char. However, in soils formed under grasslands some 40–50% of the soil organic carbon is commonly present in this form. Scientists think that such high amounts of char occur in grassland soils because of the high frequency of fires and also because mammalian burrowing activity—bioturbation—rapidly incorporates the char left on the soil surface protecting it from complete combustion in subsequent fires.

Despite its wide occurrence, scientists have largely ignored black carbon (char and the like) in their efforts to model carbon cycling in soils and analyze soil organic matter and its functions. Historically, this oversight may stem from the fact there were no simple methods to specifically measure char and the most widely used method to measure soil organic carbon (oxidation with potassium dichromate in heated strong acid) is not sensitive to char. The recognition of the importance of char really did not take off until the discovery in the central Brazilian Amazon rain forest of small patches of Terra Preta (*dark earth*) soils. These soils occurred where humans had amended the soil with char materials more than 800 years ago. Although the sites had

Figure 12.14 *Black carbon or char.* (a) *The flames of a tropical grassland fire leave the soil covered in black charred residues.* (b) *A handful of prairie surface soil with visible charred carbon.* (c) *A scanning electron micrograph (SEM) of centuries-old char from a boreal forest fire, with fungal hyphae growing in it.* [Photos courtesy of Ray R. Weil; SEM from Marie-Charlotte Nilsson Hegethorn]

[a]A number of papers review char as a natural component of soil organic matter (Hart and Luckai, 2013; Schmidt and Noack, 2000; Singh, 2012).

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BOX 12.2

CHAR: IS BLACK THE NEW GOLD? *(CONTINUED)*

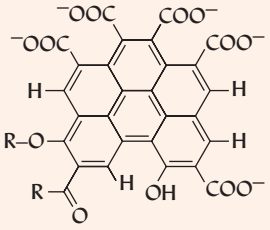

Figure 12.15 *A structural model typical for stable (partially oxidized) char depicting a molecule with six fused aromatic rings and numerous carboxylic (COO—) functional groups. This model is based on direct analysis (using quantitative 13C nuclear magnetic resonance (NMR) spectroscopy) of whole soil organic matter (not soil extracts) from both Amazonian Terra Preta soils and U.S. (Iowa) Mollisols in which about half the total organic carbon was found as char.* [Structure based on concepts in Mao et al. (2012)]

been abandoned and not seen human settlement or char inputs for many centuries, to this day the Terra Preta soils remain much darker in color and much more fertile than the surrounding Oxisols that had not been amended with char.

The carbon content of char (70–85% C) is much higher than most soil organic matter (<50% C) because much of the O and H in plant residues is lost during pyrolysis. The chemical structure of char is generally made up of a complex assortment of aromatic (double bonded hexagonal) rings (see Figure 12.15). Partial oxidation of surface aromatic rings results in many negative-charged carboxylic (COO^-) functional groups that endow the char with high cation and anion exchange capacities. The macrostructure reflects the original plant cell walls and gives the material an extremely high porosity (Figure 12.14*c*). This structure also endows char with specific surface area several times greater than that of even expansive clays—up to 2500 m^2/g (compare to values in Table 8.1). The aromatic ring structures are also very stable and resist breakdown. Although some 5–10% of char decomposes at moderate rates, most of the char is thought to be among the most long-lived soil organic components, especially when it is protected by association with mineral surfaces and inside microaggregates. The longevity of char in soils is indicated by its chemistry (resistance to decay), ^{14}C isotopic dating studies, and archaeological evidence (e.g., remains from ancient cooking fires).

The just-described characteristics of char seem much like those traditionally associated with humic substances; in fact it appears that char may be the source of some of the material found when soils are extracted for humic substances (see Box 12.3). While there is much still to learn about black carbon (char and related fire products), it is likely that in fire-prone ecosystems this material makes a major contribution to the dark soil color, high water holding capacity, reduced bulk density, and high CEC associated with soil organic matter. Where wildfires have been suppressed by humans, prescribed burns may help to maintain the char content and productivity of soils.

The protection of biomolecules from microbial degradation is important in maintaining soil organic matter levels and in protecting associated nitrogen and other essential nutrients against rapid mineralization and loss from the soil. For example, root hairs that grow into, and eventually die inside, microaggregates may be protected from decay both by physical inaccessibility to microbes and by the localized anaerobic conditions that may exist in the microaggregate interior (see Section 7.4). The stability of humus in many soils is also related to the aromatic structure of char (Box 12.2). Yet, despite such protection, the compounds that comprise humus are subject to some continual slow decomposition. Without annual additions of sufficient plant residues, slow microbial oxidation of humus results in declining levels of soil organic matter.

Clay–Humus Combinations. Interaction with clay minerals provides another means of stabilizing humus and the nitrogen it contains. Humus that is entrapped in the ultra-micropores (<1 μm) formed by clay particles is physically inaccessible to decomposing organisms (see Figure 8.32). Clay surfaces also attract and hold such substances as amino acids, peptides, and proteins, and partially oxidized lipids, forming complexes that protect these nitrogen, sulfur, and phosphorus containing compounds from microbial degradation. Although the extent and mechanisms are not yet fully understood, clay–humus interactions undoubtedly contribute to the relatively high organic matter content of soils with high clay contents (see Section 12.8).

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BOX 12.3

WHERE HAVE ALL THE HUMICS GONE?[a]

Anyone who has used drain-clearing chemicals to remove hair or grease from a clogged drain knows that strong alkali solutions (like NaOH) are very good at dissolving organic compounds that may not be soluble in water. For more than 100 years, soil scientists have used strong alkali (pH ~13) to extract organic matter from soils so they could quantify it and determine its nature in the lab (Figure 12.16). The dark-colored solutions obtained are commonly acidified and the portion of organic matter precipitated in the acid solution (pH ~1.0) is considered to be "humic acid" while the material soluble in both alkali and acid is termed "fulvic acid." The material not soluble in either acid or alkali is termed "humin", and thought to be highest in molecular weight, darkest in color, and most resistant to microbial attack. Despite a century of research on these materials collectively called "humic substances," their exact molecular structures remained elusive. However, chemists determined that humic and fulvic acids are comprised of super-sized polymers (macromolecules) with many aromatic and phenol ring structures, and with properties quite unlike any biomolecules known in plant or microbial cells. It was hypothesized that these huge, complex, and somewhat mysterious molecules were synthesized by soil microbes from plant compounds like lignin and that their sheer complexity made them "recalcitrant" or resistant to decomposition. These complex humic substances in the chemists' extractions have been credited with controlling many soil properties, including the long persistence of organic matter in soils. Analyses made using the alkali extractions indicate that 60–80% of soil organic matter existed in the form of humic substances. The term *humic substances* used to describe such molecules should not be confused with the term *humus*, which is used to describe all of the organic molecules and the very small particles of organic materials in soils that are no longer alive and no longer recognizable as tissues.

During the past two decades, new isotopic, spectroscopic, and molecular-marker analytical techniques have allowed soil chemists to study the nature of organic matter *in situ*—that is, while it is still in the soil, without having to extract it first. To their surprise, the new direct measurements found very little in the way of humic macromolecules in mineral soils. Instead, evidence suggests that the alkali extraction process itself actually creates giant polymers from smaller biomolecules. It is now thought that humic substances in soil extracts do *not* represent the nature of most of the organic material as it exists in soils. The complex humic substances that formed in the extracts do, however, have rather unique properties and may be quite bio-active. Although the effects have been quite variable, in some cases humic substances extracted from soil or, more commonly, those from mined partially fossilized organic deposits (termed **humates**), may considerably enhance certain aspects of plant growth when sprayed on the plants or used as soil amendments (see Section 12.5).

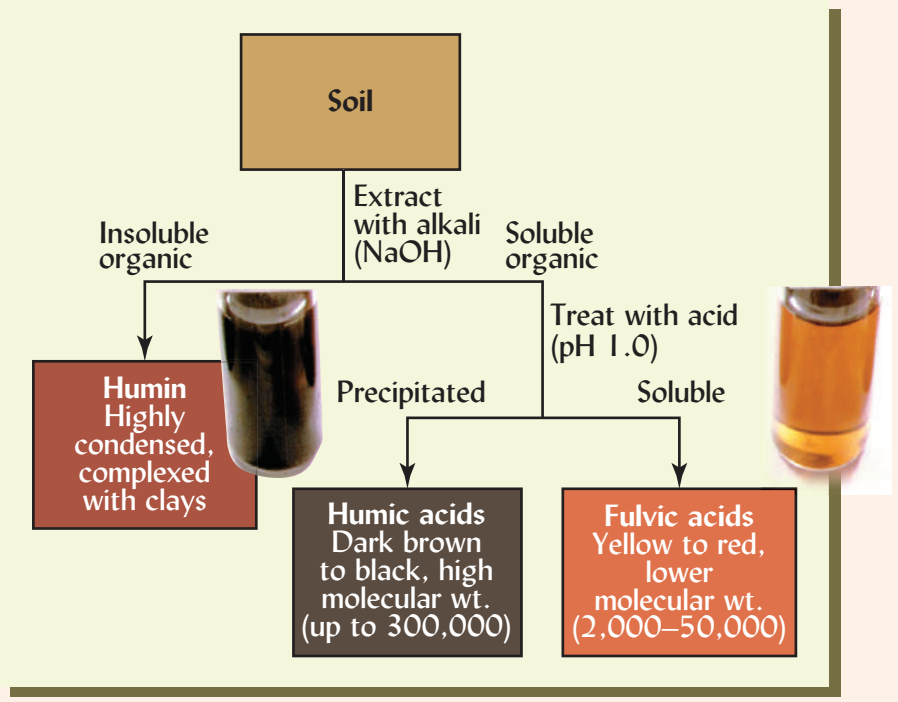

Figure 12.16 *The traditional scheme for classifying so-called humic substances found to occur in highly alkaline extractions of soil.* (Diagram courtesy of Ray R. Weil)

[a]For a detailed historical and chemical explanation of this view of humic substances, see Kleber and Johnson (2010).

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12.5 INFLUENCES OF ORGANIC MATTER ON PLANT GROWTH AND SOIL FUNCTION

Long ago, the observation that plants generally grow better on organic-matter-rich soils led people to think that plants derive much of their nutrition by absorbing humus (organic carbon) from the soil. We now know that vascular plants derive their carbon from carbon dioxide and that most of their nutrients come from inorganic ions dissolved in the soil solution. In fact, plants can complete their life cycles growing totally without humus, or even without soil (as in soilless or **hydroponic** production systems using only aerated nutrient solutions). This is not to say that soil organic matter is less important to plants than was once supposed, but rather that most of the benefits accrue to plants indirectly through the many influences of organic matter on soil properties. These will be discussed later in this section, after we consider two types of direct organic matter effects on plants.

Direct Influence of Humus on Plant Growth

It is well established that certain organic compounds are absorbed by higher plants. For example, plants can absorb a varying proportion of their nitrogen and phosphorus needs as soluble organic compounds. In addition various growth-promoting compounds such as vitamins, amino acids, and hormones (e.g., auxins and gibberellins) are formed as organic matter decays. These substances may at times stimulate growth in both higher plants and microorganisms.

Small quantities of both fulvic and humic acids added to soils are known to enhance certain aspects of plant growth (Table 12.4). Some evidence suggests that the application of mined humic substances can stimulate plant growth by improving the availability of micronutrients, especially iron and zinc. Small biomolecules, such as citric acid, dissolved in the soil solution can have similar effect on micronutrient availability. Some scientists suggested that the humic substances may act as hormone-like regulators of specific plant-growth functions such as cell elongation or lateral root initiation. Several plant hormones, including indoleacetic acid (IAA) and isopentenyladenosine (a cytokinin), have been isolated from humic substances in alkaline extracts of mined lignite (a coal-like carbonaceous deposit) and earthworm casts. It is possible that small amounts of somewhat similar humic substances are dissolved in the soil solution in some soils. Such humic substances may have some practical potential as soil amendments or plant growth stimulants (see Figure 12.17).

The concentrations of humic substances commonly present in the soil solution in humid regions (50–100 mg/L or ppm) are effective in stimulating plant growth. Commercial humate products (solid salts of humic acid) are marketed with claims that small amounts enhance plant growth, but scientific tests of many of these products have given very mixed results, often showing no benefit from their use on soils well endowed with organic matter. The lack of amendment effects may be due to the natural presence in most soils of humic substances or their active components at levels sufficient to carry out the desired functions.

Table 12.4
SOME DIRECT EFFECTS OF HUMIC SUBSTANCES ON PLANT GROWTH

Effect on plant growth	Humic substance	Concentration range, mg/L
Accelerated water uptake and enhanced germination of seeds	Humic acid	1–100
Stimulated root initiation and elongation	Humic and fulvic acids	50–300
Enhanced root cell elongation	Humic acid	5–25
Enhanced growth of plant shoots and roots	Humic and fulvic acids	50–300

From Chen and Aviad (1990).

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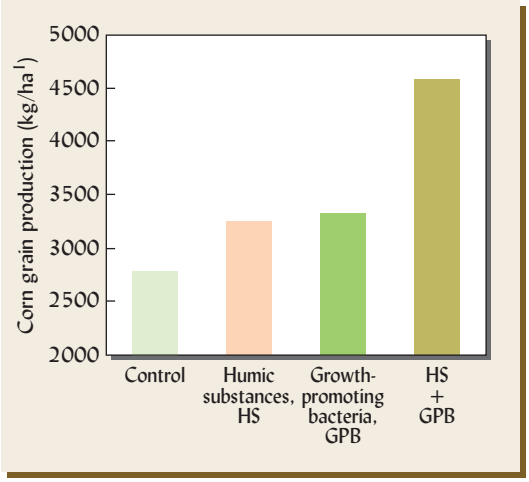

Figure 12.17 *Synergistic effect of spraying a field corn crop with humic substances (HS) from vermicompost extracts and growth promoting bacteria (GPB) under low nitrogen fertility (all plots received just 50 kg N/ha as fertilizer). Either the HS or the GPB added alone increased yield by ~500 kg/ha, but the two components added together increased yield by almost 1800 kg/ha compared to the control. The HS were from extracts of vermicomposted (earthworm worked) manure applied at about 6 g carbon /ha. The GPB were* Herbaspirillum seropedicae*, a nitrogen fixing and growth-stimulating species that colonizes grass plant roots. It is thought that the HS altered the maize root growth in a way that made colonization easier for the bacteria. The soil was a low fertility Ultisol in Brazil.* [Graphed from data in Canellas et al. (2013)]

Allelochemical Effects[5]

Allelopathy is the process by which one plant infuses the soil with a chemical that affects the growth of other plants. The plant may do this by directly exuding **allelochemicals**, or the compounds may be leached out of the plant foliage by throughfall rainwater. In other cases, microbial metabolism of dead plant tissues (residues) forms the allelochemicals. The term *allelochemical* is also applied to plant chemicals that inhibit microorganisms. In principle, the interactions are much like the antagonistic relationships among certain microorganisms discussed in Section 11.14. In fact, allelochemicals often serve several different functions in the rhizosphere and the concept overlaps with that of "signaling" chemicals, which plants use to communicate with other plants certain soil organisms (Section 11.7).

Allelochemicals present in the soil are apparently responsible for many of the effects observed when various plants grow in association with one another. Because they produce such chemicals, certain weeds (e.g., Johnsongrass and giant foxtail) damage crops far out of proportion to the size and number of weeds present. Crop residues left on the soil surface may inhibit the germination and growth of the next crop planted (e.g., wheat residues often inhibit sorghum plants). Farmers may select such cover crops as rye or rapeseed, in part, because of the inhibiting effect the allelochemicals from their residues may have on weed seed germination.

Other allelopathic interactions influence competition and the succession of species in natural ecosystems. Allelopathy may be partially responsible for the invasiveness of certain exotic plant species that rapidly dominate a new ecosystem to which they have been recently introduced. The invaders' allelochemicals may be more effective in the new ecosystem than they were in their territory of origin where neighboring plant species had time to evolve tolerance.

Allelopathic interactions are usually very specific, involving only certain species, or even varieties, on both the producing and receiving ends (Figure 12.18). The effects of allelopathic chemicals are many and varied. Although the term *allelopathy* most commonly refers to negative effects, allelochemical effects can also be positive (as in certain **companion plantings**). Because most of the active compounds can be rapidly destroyed by soil microorganisms or easily leached out of the root zone, effects are usually relatively short-lived once the source is removed. While they vary in composition, most allelochemicals are relatively simple phenolic or organic acid compounds that could be included among the biomolecules found in the labile carbon pool of soil organic matter.

[5]For a review of allelopathy as it relates to plants and soil microbes, see Cipollini et al. (2012). For roles of allelopathy in plant species invasiveness and community ecology, see Inderjit et al. (2011).

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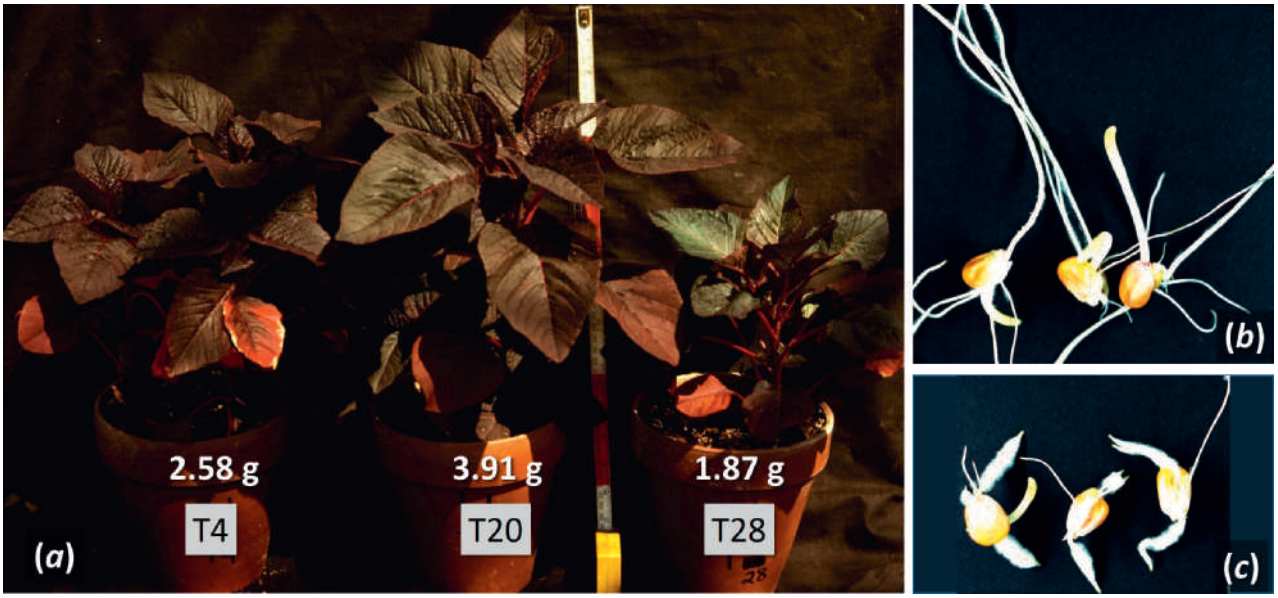

Figure 12.18 *Variable and genotype specific nature of allelopathy.* (a) *Positive and negative allelopathic effects of winged bean on grain amaranth plants. The average dry weight of the amaranth plants for each treatment is shown. All pots were watered with a complete nutrient solution so any nutrients from the winged bean should not have had an effect. In the pot on the left (T4) amaranth is growing in fresh soil (no association with winged bean). In the center pot (T20) amaranth is growing in soil previously used to grow winged bean (positive effect). In the pot on the right (T28) the amaranth is growing in fresh soil, but the plant was watered three times with a water extract of winged bean tissue (negative effect).* (b) *Corn seeds germinated with a water extract of leaves from a Thai variety of winged bean.* (c) *Corn seeds germinated with a water extract of leaves from a Sri Lankan variety of winged bean.* (Photos courtesy of Ray R. Weil)

Influence of Organic Matter on Soil Properties and Indirectly on Plants[6]

Soil organic matter affects so many soil properties and processes that a complete discussion of the topic is beyond the scope of this chapter. Indeed, in almost every chapter in this book there is mention of the roles of soil organic matter. Figure 12.19 summarizes some of the more important effects of organic matter on soil properties and on soil–environment interactions. Often one effect leads to another, so that a complex chain of multiple benefits results from the addition of organic matter to soils. For example (beginning at the upper left in Figure 12.19), adding organic mulch to the soil surface encourages earthworm activity, which in turn leads to the production of burrows and other biopores, which in turn increases the infiltration of water and decreases its loss as runoff, a result that finally leads to less pollution of streams and lakes.

Influence on Soil Physical Properties. Humus tends to give surface horizons dark brown to black colors. Granulation and aggregate stability are encouraged, especially by the bacteria polysaccharides and fungal glomalin-associated glycoproteins produced during decomposition (see Section 4.5). The protected particulate organic matter, char, and sorbed biomolecules in the humus help reduce the plasticity, cohesion, and stickiness of clayey soils, making these soils easier to manipulate.

A major reason why soils higher in organic matter tend to be more productive is their enhanced ability to supply plants with water because organic matter increases both infiltration rate and water-holding capacity. Organic matter has an especially pronounced

[6]For a readable introduction to increased soil organic matter improves soils physically, chemically, and biologically, see Blanco-Canqui et al. (2013).

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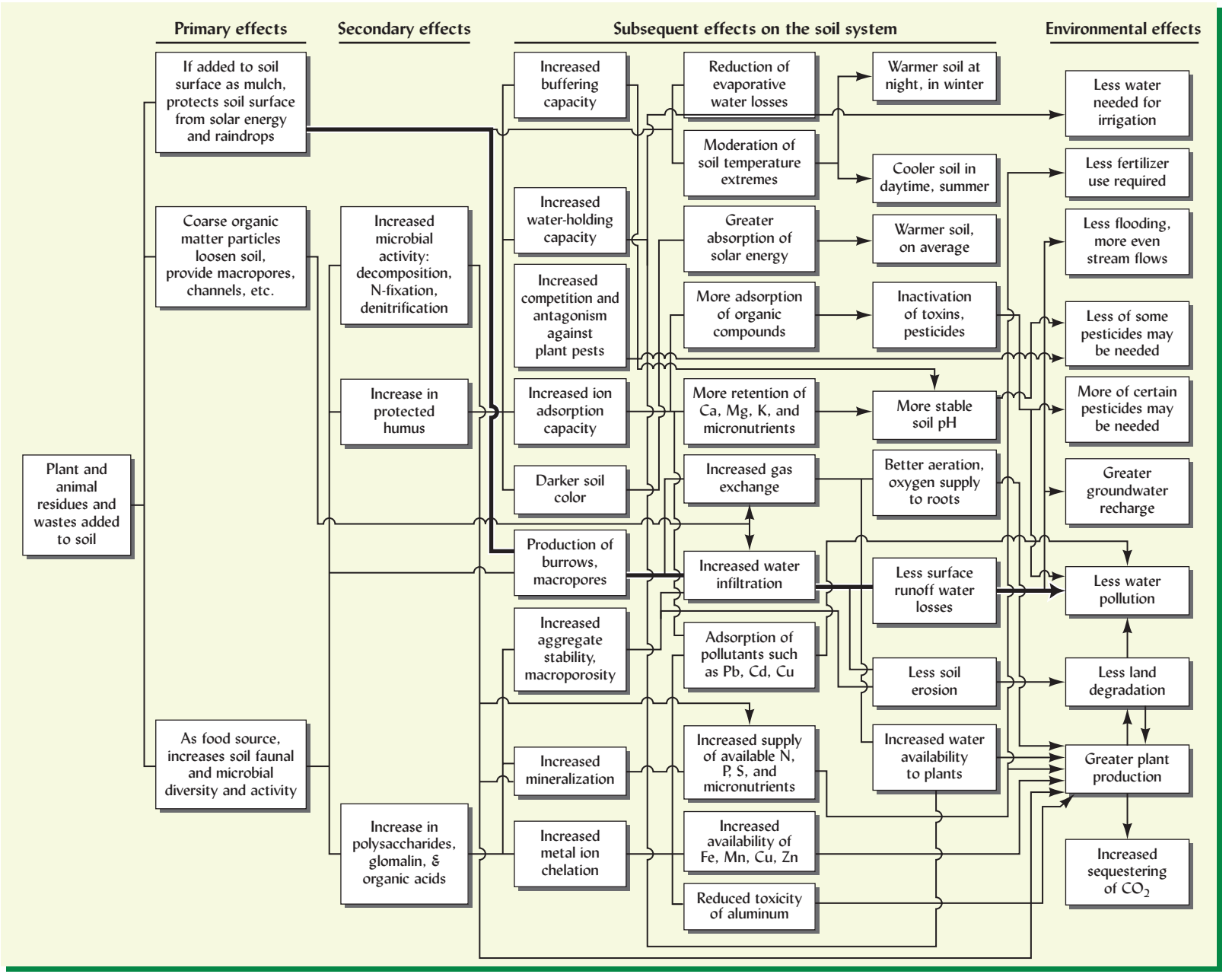

Figure 12.19 *Some of the ways in which soil organic matter influences soil properties, plant productivity, and environmental quality. Many of the effects are indirect, the arrows indicating the cause-and-effect relationships. It can readily be seen that the influences of soil organic matter are far out of proportion to the relatively small amounts present in most soils. Many of these influences are discussed in this and other chapters in this book. The thicker line shows the sequence of effects referred to in the text in this section. It will be worthwhile to follow the paths of other chains of cause and effect shown, stopping to ask yourself whether the connections make sense with respect to what you have learned in other parts of this book.* (Diagram courtesy of Ray R. Weil)

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effect on the water-holding capacity of very sandy soils, which can often be improved by adding stable organic amendments. Improved water retention is a major reason why sand-based golf greens are commonly amended and top-dressed with peat (Figure 12.20). However, the use of large amounts of peat mined from sphagnum wetlands cannot be considered environmentally sustainable (see Box 12.4), so compost made from various organic wastes (Sections 11.13 and 12.10) would be a more environmentally responsible amendment for this use.

Influence on Soil Chemical Properties. Humus generally accounts for 50–90% of the cation-adsorbing power of mineral surface soils. Like clays, humus colloids and high surface area char hold nutrient cations (potassium, calcium, magnesium, etc.) in easily exchangeable form, wherein they can be used by plants but are not too readily leached out of the profile by percolating waters. Through its cation exchange capacity and acid and base functional groups, organic matter also provides much of the pH buffering capacity in soils (see Section 9.4). In addition, nitrogen, phosphorus, sulfur, and micronutrients are stored as constituents of soil organic matter, from which they are slowly released by mineralization.

Organic acids also attack soil minerals and accelerate their decomposition, thereby releasing essential nutrients as exchangeable cations. Small molecular weight organic acids, as well as polysaccharides and certain polar biomolecules are especially effective in attracting such cations as Fe^{3+}, Cu^{2+}, Zn^{2+}, and Mn^{2+} from the edges of mineral structures and **chelating** or binding them in stable organomineral complexes. Some of these metals are made more available to plants as micronutrients because they are kept in soluble, chelated form (see Chapter 15). In very acid soils, organic matter alleviates aluminum toxicity by binding the aluminum ions in nontoxic complexes (see Sections 9.2 and 9.9).

Biological Effects. Soil organic matter—especially the detritus fraction—provides most of the food for the community of heterotrophic soil organisms described in Chapter 11. In Section 12.3 it was shown that the quality of plant litter and soil organic matter markedly affects initial decomposition rates. The type and diversity of organic residues added to a soil can influence the type and diversity of organisms that make up the soil community (as discussed in Section 11.14).

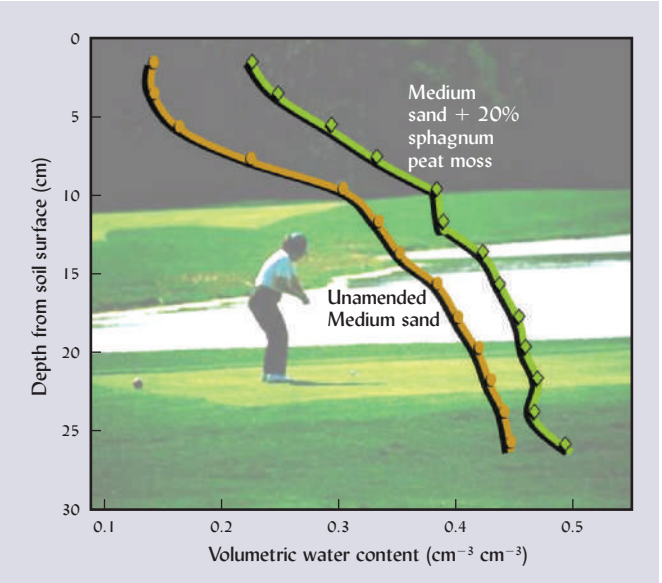

Figure 12.20 *Effect of organic amendment on soil water retention. Columns 30 cm tall were filled with medium-sized sand of the type used for the root zone in golf course greens. The sand in some columns was mixed with peat (20% by volume). The columns were saturated with water and allowed to drain freely for 24 hours before the volumetric water was measured. While both columns were near 100% saturation at the lowest depth (where the water potential was near zero, see Section 5.3), the peat more than doubled the water held in the upper part of the profile.* [Redrawn from data in Bigelow et al. (2004)]

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12.6 AMOUNTS AND QUALITY OF ORGANIC MATTER IN SOILS[7]

Active Organic Matter

The organic matter of the labile carbon pool is sometimes referred to as **active soil organic matter** as it consists of labile (easily decomposed) materials with half-lives (the time it takes for half of a mass of material to decay) of only a few weeks to a few years. Active soil organic matter still has a relatively high average C/N ratio (about 15–30) and includes such organic matter fractions as the living biomass, tiny pieces of unprotected detritus (the free POM), and many biomolecules as described in Section 12.4. Active organic matter rarely comprises more than 10–20% of the total soil organic matter.

The active organic matter provides most of the readily accessible food for soil organisms and most of the readily mineralizable nitrogen. It is responsible for most of the beneficial effects on structural stability that lead to enhanced infiltration of water, resistance to erosion, and ease of tillage. The active organic matter can be readily increased by the addition of fresh plant and animal residues, but it is also very readily lost when such additions are reduced or tillage is intensified.

Passive Organic Matter

The more stable and well-protected portion of the humus fraction is often referred to as passive organic matter because its carbon is not readily accessible to microbes and remains in the soil for hundreds or even thousands of years. This pool includes most of the humus physically protected in clay–humus complexes, POM protected inside microaggregates, and chemically stable bits of char. Passive organic matter accounts for 60–90% of the organic matter in most soils, and its quantity is increased or diminished rather slowly. Passive organic matter is most closely associated with the colloidal properties of soil humus and is responsible for most of the cation- and water-holding capacities contributed to the soil by organic matter.

Some models divide the organic matter further, distinguishing a **slow pool** of soil organic matter with properties intermediate between the active and passive pools and half-lives typically measured in decades. However, it should be remembered that these pools are determined more by the environmental conditions and microbial community in a soil, than by the chemistry of its constituents. For example, experiments have shown that under warm conditions a greater proportion of a soil's carbon will turn over at rates rapid enough to be characterized as active organic matter than would be the case when the same soil is kept cold.

Changes in Active and Passive Pools with Soil Management

Although it usually is not practical to accurately isolate and measure the organic materials in the active, slow, and passive pools of soil organic matter, analytical methods are available to evaluate chemical or physical fractions of soil organic matter that contribute to these functionally defined pools. Soil scientists have consistently observed that productive soils managed with conservation-oriented practices contain relatively high amounts of organic matter fractions associated with the active pool, including microbial biomass, free particulate organic matter, and easily oxidizable organic matter (see, e.g., Table 20.8).

Despite the analytical difficulties and conditional definitions, computer models that assume the existence of active and passive pools have proven quite useful in explaining and predicting real changes in soil organic matter levels and in attendant soil properties. Studies on the dynamics of soil organic matter have established that the different pools of soil organic matter play quite different roles in the soil system and in the carbon cycle. The presence of a resistant (structural) pool of carbon in plant residues, as well as an easily decomposed (metabolic) pool, explains the initially rapid but decelerating rate of decay that occurs when plant tissues are added

[7]For a review of simulation models that predict changes in soil organic matter, see Campbell and Paustian (2015).

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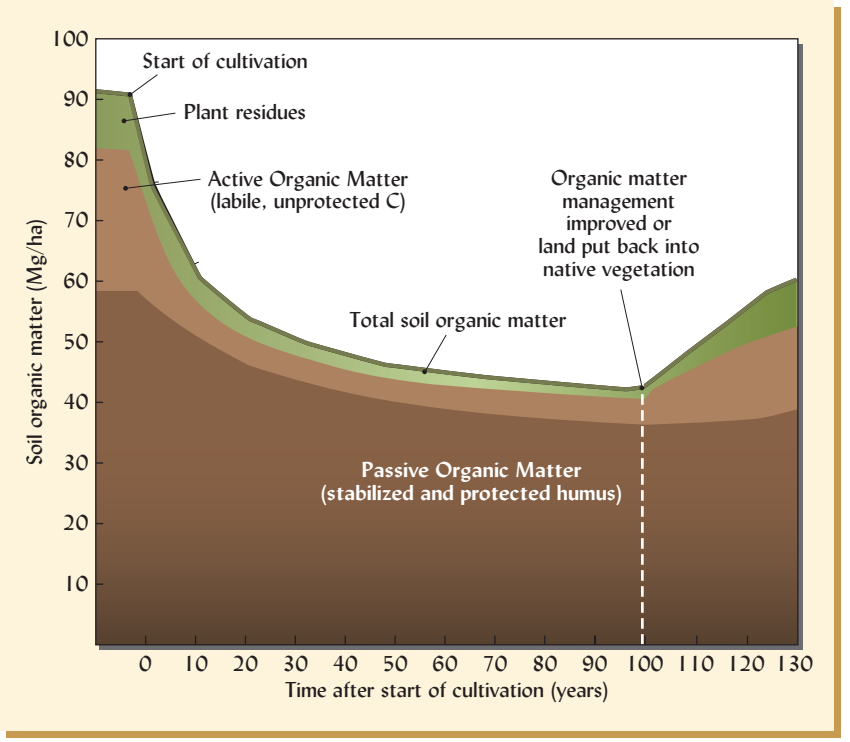

Figure 12.21 *Changes in soil organic matter in the upper 30 cm of a representative soil after bringing virgin land under cultivation. Initially, the rapidly decomposing active or labile pool accounted for about 23 Mg, or about 25% of the total soil organic matter. After about 50 years of cultivation, the passive pool had declined by about 30% from 91 to about 40 Mg/ha, while the active pool had lost 90% of its mass, declining to only 2 Mg/ha. Thus most of the organic matter loss came from the active pool. This was also the pool that most quickly increased when improved management was adopted after the 100th year. This behavior explains why even relatively small changes in total soil organic matter can produce dramatic changes in soil properties, such as aggregate stability and nitrogen mineralization.* (Diagram courtesy of Ray R. Weil)

to a soil (see Figures 12.5 and 12.6). Similarly, the existence of a pool of chemically or physically protected soil organic matter (passive pool), as well as a pool of easily metabolized soil organic matter (active pool), explains why conversion of native forests or grassland into cultivated cropland results in a very rapid decline in soil organic matter during the first few years, followed by a much slower decline thereafter (see, e.g., Figure 12.21). However, it is widely acknowledged that such models will need to be improved with better consideration of the roles of black carbon (char), root deposition (as opposed to surface litter), and changes in soil conditions such as aggregation and temperature that can shift the "boundaries" of the pools themselves.

Soil management practices that cause only small changes in total soil organic matter often cause rather pronounced alterations in aggregate stability, nitrogen mineralization rate, or other soil properties attributed to organic matter. This occurs because the relatively small pool of active organic matter may undergo a large percentage increase or decrease without having a major effect on the much larger pool of total organic matter. Figure 12.21 shows how the pools of soil organic matter are affected by changing management (in this case, cultivating a previously undisturbed soil). The figure also indicates how each pool contributes to the total soil organic matter level.

Accumulated plant residues and active organic matter are the first to be affected by changes in land management, accounting for most of the early losses in soil organic matter when cultivation of virgin soil begins. In contrast, losses from the passive pool are more gradual. As a result, the soil organic matter remaining after some years is far less effective in promoting structural stability and nutrient cycling than the original organic matter in the virgin soil. If a favorable change in environmental conditions or management regime occurs, the plant litter and active pools of soil organic matter are also the first to positively respond (see right-hand portion of Figure 12.21).

12.7 CARBON BALANCE IN THE SOIL–PLANT–ATMOSPHERE SYSTEM

Whether the goal is to mitigate climate change by sequestering carbon and reducing greenhouse gas emissions, or to enhance soil quality and plant production, proper management of soil organic matter requires an understanding of the factors and processes influencing

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the cycling and balance of carbon in an ecosystem. Although each type of ecosystem—forest, prairie, wetland, or wheat field—will emphasize particular compartments and pathways in the carbon cycle, consideration of a specific example, such as that described in Box 12.4, can help us develop a conceptual model that can be applied to many different situations.

The rate at which soil organic matter either increases or decreases largely depends on the balance between *gains* and *losses* of carbon. In this regard, the level of SOM is analogous to the level of water in a bathtub, which is determined by the rates of inflow through the faucet and outflow through the drain. If the drain is fully opened, the water level will be low—even if the faucet is turned on fully. In soils, the organic matter gains come primarily from plant residues and exudates grown in place and from applied organic materials (in managed soils). The losses are due mainly to respiration (CO_2 emissions), erosion, leaching of dissolved C, and (in managed soils) plant removals (Figure 12.22). Table 12.5 provides some practical strategies for maximizing these gains and minimizing these losses so as to achieve increased soil organic matter in managed terrestrial ecosystems such as urban landscapes, croplands, forest plantations, and pastures or rangelands.

Agroecosystems

Conservation of Soil Carbon. In order to halt or reverse the net carbon loss shown in Figure 12.24, management practices would have to be implemented that would either *increase the additions* of carbon to the soil or *decrease the losses* of carbon from the soil. Since all crop residues and animal manures in the example are already being returned to the soil, additional carbon inputs could most practically be achieved by growing more plant material (i.e., increasing crop yields or growing cover crops during the winter).

Specific practices to reduce carbon losses would include better control of soil erosion and the use of conservation tillage. Using a no-till production system would leave crop residues as mulch on the soil surface where they would decompose much more slowly. Refraining from tillage might also reduce the annual respiration losses from the original 2.5% to perhaps 1.5%. A combination of these changes in management would convert the system in our example from one in which soil organic matter is degrading (declining) to one in which it is accumulating (increasing).

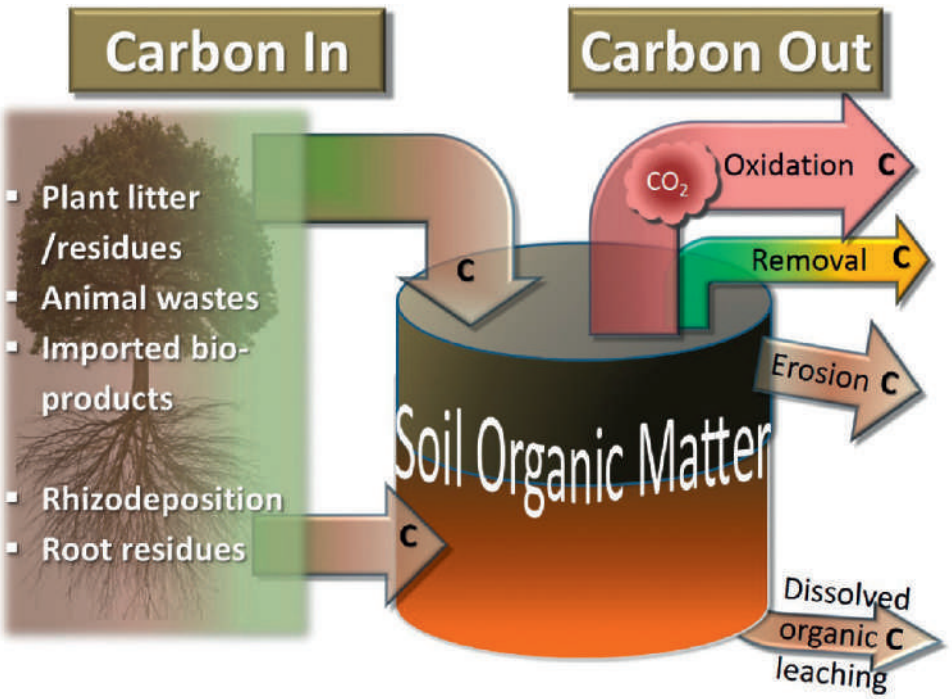

Figure 12.22 *The level of organic matter present in a soil is largely determined by the balance between carbon in and carbon out. Soil management therefore needs to focus on strategies to maximize the inputs and minimize outputs, with the exception of the necessary economic harvest removals. Some practices appropriate for these strategies are listed in Table 12.5.* (Diagram courtesy of Ray R. Weil)

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BOX 12.4

CARBON BALANCE—AN AGROECOSYSTEM EXAMPLE

The principal carbon pools and annual flows in a terrestrial ecosystem are illustrated in Figure 12.23 using a hypothetical cornfield in a warm temperate region. During a growing season the corn plants produce (by photosynthesis) 17,500 kg/ha of dry matter containing 7500 kg/ha of carbon (C). This C is equally distributed (2500 kg/ha each) among the roots, grain, and unharvested aboveground residues. In this example, the harvested grain is fed to animals, which oxidize and release as CO_2 about 50% of this C (1250 kg/ha), assimilate a small portion as weight gain, and void the remainder (1100 kg/ha) as manure. The corn stover and roots are left in the field and, along with the manure from the animals, are incorporated into the soil by tillage or by earthworms.

The soil microbes decompose the crop residues (including the roots) and manure, releasing as CO_2 some 75% of the manure C, 67% of the root C, and 85% of the C in the surface residues. The remaining C in these pools is assimilated into the soil organic matter. Thus, during the course of one year, some 1475 kg/ha of C enters the SOM pool (825 kg from roots, plus 375 from stover, plus 275 from manure). These values are in general agreement with Figure 12.13, but they will vary widely among different soil conditions and ecosystems.

At the beginning of the year, the upper 30 cm of soil in our example contained 65,000 kg/ha C in soil organic matter. Such a soil cultivated for row crops in a temperate region would typically lose about 2.5% of its organic C by soil respiration each year. In our example this loss amounts to some 1625 kg/ha of C. Smaller losses of soil organic C occur by soil erosion (160 kg/ha), leaching (10 kg/ha), and formation of carbonates and bicarbonates (10 kg/ha).

Comparing total losses (1805 kg/ha) with the total gains (1475 kg/ha), we see that the soil in our example suffered a net annual loss of 330 kg/ha of C, or 0.5% of the total C stored in the organic matter soil. If this rate of loss were to continue, degradation of soil quality and productivity would surely result.

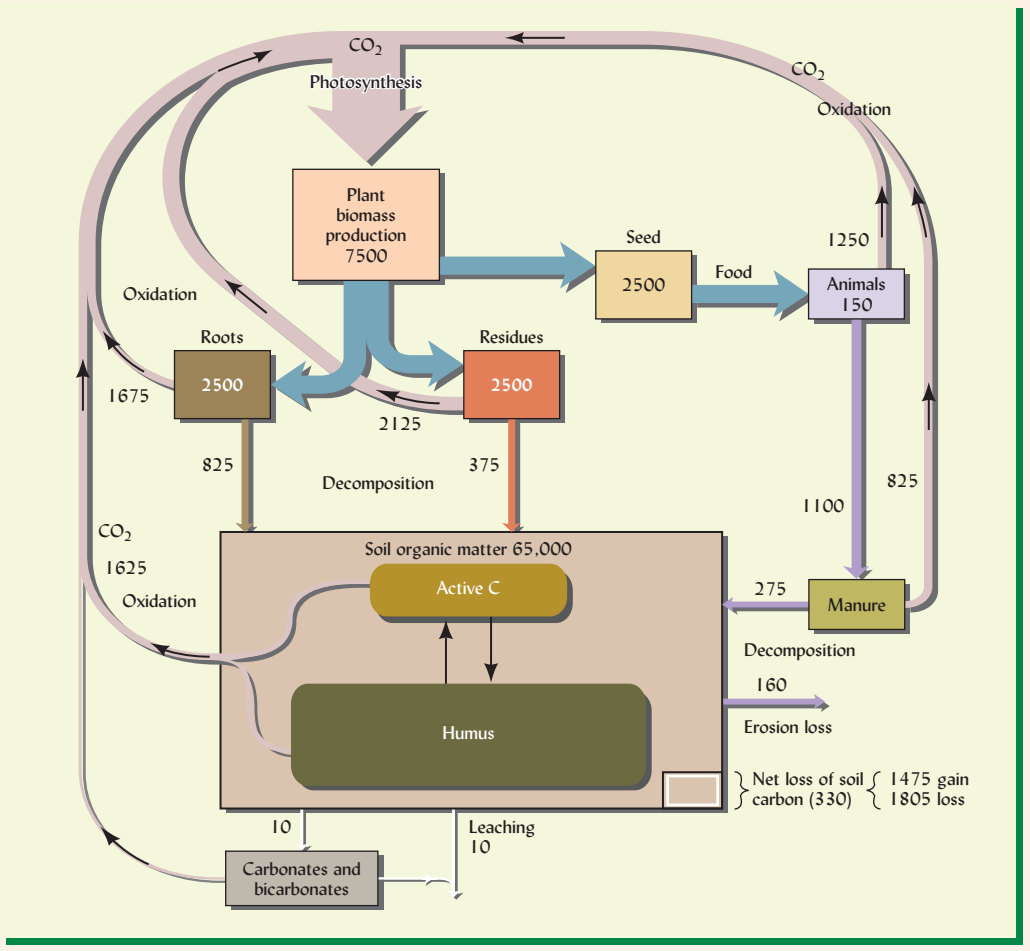

Figure 12.23 *Carbon cycling in an agroecosystem.* (Diagram courtesy of Ray R. Weil)

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Table 12.5
How to Maintain a Positive Balance Between Gains and Losses of Organic Matter
Most of these practices will improve soil quality as well as increase carbon stored in soils.

Inputs	Specific practices to maximize	Losses	Specific practices to minimize
Aboveground plant residues	• Return all residues • Fertilize with sufficient nutrients for high net production • Optimize plant spacing, varieties, timing • Add cover crops for off-season growth • Grow more perennials rather than annuals • Use complex crop rotations • Manage grazing/mowing to maximize plant production • Manage fire to maximize char	**Oxidation**	• Reduce or eliminate tillage • Moderate soil temperature (mulch or moisture) • Grow plants with recalcitrant litter • Grow deep rooted plants • Grow high root/shoot ratio plants • Mulch rather than incorporate organic amendments • Avoid excessive nitrogen fertilizer • Pyrolyze organic wastes to make biochar before applying to soils • Manage fire to minimize combustion losses
Animal inputs	• Recycle manure and bedding • Urine and manure from grazing	**Removal**	• Remove only economic plant parts • Mulching-mow turf to leave clippings
Recycled offsite biomaterials	• Apply bio-wastes from food, biofuels, and forestry industries • Sewage sludge (biosolids) application • Use composted municipal solid wastes • Apply organic mulch • Biochar application	**Erosion**	• Use no-till • Use surface mulches • Grow cover crops between cash crops seasons • Grow perennial cover crops between tree rows • Grow more perennial crops • Use terraces, grassed water ways, etc.
Root residues	• Plant high root biomass crops • Grow more perennials rather than annuals • Controlled grazing/mowing to maximize root growth	**Leaching**	• Maximize evapotranspiration during wet periods • Grow cover crops • Manage soil water • Manage plants for root exudates • Manage for mycorrhiza
Rhizodeposition	• Manage plants for enhanced root growth and deposition • Manage soil microbial community		

Natural Ecosystems

Upland Forests. Those interested in natural ecosystems may want to compare the carbon cycle of a natural forest with that of the cornfield in Figure 12.23. If the forest soil fertility were not too low, the total annual biomass production would probably be similar to that of the cornfield. The standing biomass, on the other hand, would be much greater in the forest since the tree crop is not removed each year. While some litter would fall to the soil surface, much of the annual biomass production would remain stored in the woody tissue of the trees.

The rate of organic matter oxidation in the undisturbed forest would be considerably lower than in the tilled field because the litter would not be incorporated into the soil through tillage, and the absence of physical disturbance would result in slower soil respiration. The litter from certain tree species may also be rich in phenolics and lignin, factors that greatly slow initial decomposition and C losses (see Figure 12.10). In forest soils, decomposition of leaf litter produces

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copious quantities of DOC compounds such as organic acids and tannins, so 5–40% of the total C losses may occur by leaching—a much greater proportion than from all but the most heavily manured cropland soils. However, losses of organic matter through soil erosion would be much smaller on the forested site. Taken together, these factors allow annual net gains in soil organic matter in a young forest and maintenance of high soil organic matter levels in mature forests.

Grasslands. Similar trends occur in natural grasslands, although the total biomass production is likely to be considerably less, depending mainly on the annual rainfall. Among the principles illustrated in Box 12.4, and applicable to most ecosystems, is the dominant role that plant root biomass plays in maintaining soil organic matter levels. In grassland, the contribution from the plant roots is relatively more important than in a forest. A relatively large proportion of the net annual productivity from perennial grass occurs below ground as root growth, regeneration, and exudation (see Section 11.7). This belowground plant biomass tends to decay more slowly than above ground residues. Therefore, a greater proportion of the total biomass produced tends to accumulate as soil organic matter, and this soil organic C is distributed more uniformly with depth under grassland than under forest vegetation.

Another factor influencing accumulation of C in grassland soils and not considered in Box 12.4, is the frequent occurrence of fire. Fires that burn dead aboveground plant material are usually thought to reduce soil organic matter inputs to the soil, but in perennial grasslands studies have shown that increased root growth stimulated by the fires may contribute at least as much carbon to the soil as that lost in the blaze itself. Also, while fire instantly converts even lignacious organic C into CO_2, fires also produce varying amounts of slow-to-decompose char (see Box 12.2).

Wetlands. Wetlands, whether dominated by woody or herbaceous vegetation, exhibit among the highest levels of primary productivity of any ecosystems. However, microbial decomposition is severely retarded by lack of oxygen in the strongly anaerobic wetland soils. In addition, certain products of anaerobic decay (alcohols, organic acids, etc.) actually act as preservatives and inhibit even anaerobic organisms. As a result, organic carbon accumulates rapidly (300–3000 kg/ha annually) and may continue to do so for thousands of years in some cases (see Sections 7.7 and 11.9). This prodigious level of carbon sequestration can be reduced or even reversed by practices, such as ditching, drainage, or peat mining, that increase the soil's oxygen content. Converting wetlands to agricultural use, except perhaps for some types of flooded rice or cranberry production, dramatically increases losses and decreases gains of carbon. The effect of prescribed burning on marsh soil carbon is still under study, but may be similar to that just described for grasslands.

12.8 ENVIRONMENTAL FACTORS INFLUENCING SOIL ORGANIC CARBON LEVELS

As just indicated in Section 12.7, the extent to which organic matter accumulates in soils is determined by the balance of gains and losses of organic carbon. Three environmental factors stand out in broadly determining the *concentration* of organic carbon in surface soils; these are *temperature*, *moisture*, and *soil texture.* When soil organic carbon *stocks*—the amount stored per unit area of land surface are considered, then soil depth distribution is a fourth major determining factor. In this section we will examine how these factors—and related biological and management factors influence the patterns and extent of organic carbon accumulation in soils.

Differences Among Soil Orders

Even though SOC contents vary as much as tenfold within a single soil order, a few generalizations are possible. In considering these, it will be instructive to compare the global soil carbon map (Figure 12.24) with the global soil orders map (front end papers) as well as to review the soil order descriptions in Chapter 3. Aridisols (dry soils) are generally the lowest in organic matter,

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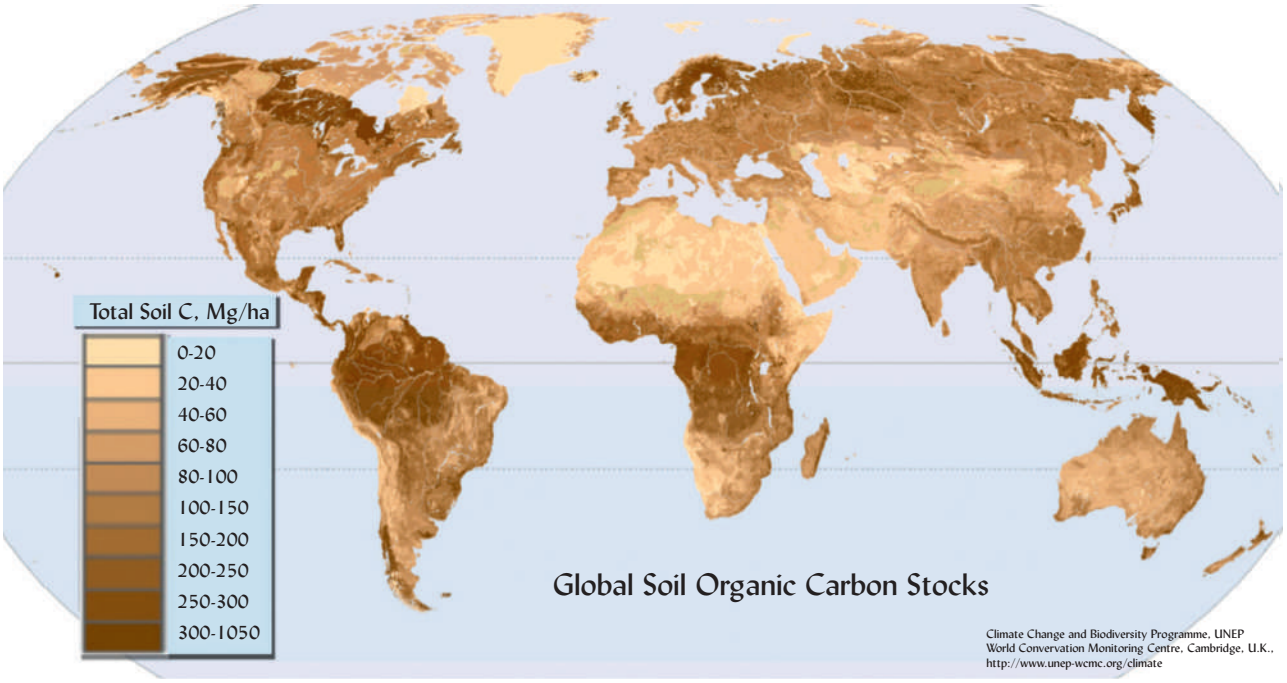

Figure 12.24 *Global distribution of organic carbon in the upper 1 m of the Earth's soils. The influences of temperature and moisture (as a function of annual precipitation/potential evapotranspiration and topographic wetness) and are well illustrated. The dark brown areas in the artic show the importance of Histosols and Gelisols as major repositories of organic C and illustrate the influence of cold temperatures, often combine with waterlogged soils. The dark brown areas in the tropics (mainly the Amazon, Congo, and Indonesian rain forests) illustrate the impact of high rainfall and resulting vegetative productivity. In contrast the light colored areas in North Africa and Central Asian illustrate how hot and dry conditions produce desert soils very low in organic carbon.* [Adapted from Scharlemann et al. (2010)]

and Histosols (organic soils) are definitely the highest (compare Figures 3.21 and 3.28). Contrary to popular myth, forested soils in humid tropical regions (e.g., Oxisols and some Ultisols) contain similar concentrations organic carbon to those in humid temperate regions (e.g., Alfisols and Spodosols). Andisols (volcanic ash soils) generally have some of the highest organic carbon contents of any mineral soils, probably because association with allophane clay in these soils protects the organic carbon from oxidation (see Figure 3.17). Among cultivated soils in humid and subhumid regions, Mollisols (prairie soils) are known for their dark, organic, carbon-rich surface layers (see Figure 3.33). The amount of SOC in mineral surface soils thus varies from a mere trace (sandy, desert soils) to as high as 10 or 20% (some forested or poorly drained A horizons) and up to 50% in some Histosols.

Most aboveground organic residues in both cultivated and undisturbed soils are incorporated in, or deposited on, the soil surface. Therefore, organic matter tends to accumulate in the upper layers with much lower organic carbon contents in the subsurface horizons (Figure 12.25). Note that the organic carbon content decreases less abruptly with depth in grassland soils than in forested ones, because much of the annual carbon addition in grasslands comes in the form of fibrous roots extending deep into the profile (see Section 2.6). In forest ecosystems, deep soil profiles may also hold a substantial amount of carbon below the A horizons, as can be calculated by simply multiplying the rather low carbon concentrations in the subsoil by the very large volume of these deep soil layers.

Influence of Climate

Temperature. Like any biological process, the respiration loss of soil carbon takes place at increasing rates as soil temperatures increase. The temperature response is thought to be greater for respiration of labile soil carbon than for carbon in the more protected or resistant humus fractions (Figure 12.26). The data also show that temperature response interacts with soil

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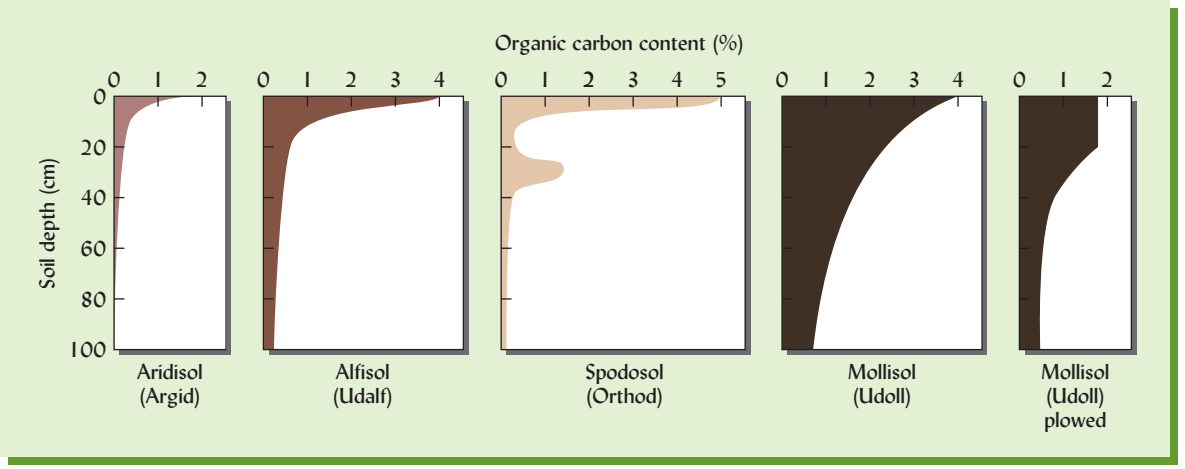

Figure 12.25 *Vertical distribution of organic carbon in well-drained soils of four soil orders. Note the higher content and deeper distribution of organic carbon in the soils formed under grassland (Mollisols) compared to the Alfisol and Spodosol, which formed under forests. Also note the bulge of organic carbon in the Spodosol subsoil due to illuvial humus in the spodic horizon (see Figure 3.3). The Aridisol has very little organic carbon in the profile, as is typical of dry-region soils.* (Diagram courtesy of N. C. Brady and Ray R. Weil)

moisture, being small when water is limiting, and also declining when soils are so wet that oxygen becomes limiting to the process.

The processes of organic matter production (plant growth) and destruction (microbial decomposition) respond differently to increases in temperature. Figure 12.27 shows that at low temperatures, plant growth outstrips decomposition and organic matter accumulates. However, the opposite is true where mean annual temperature exceeds approximately 25–35 °C. At high temperatures, decomposition surpasses plant growth, so nutrient release is rapid, but organic matter accumulation is lower than in cooler soils. Some of the most rapid rates of organic matter decomposition occur in irrigated soils of hot desert regions.

Within zones of comparable moisture and vegetation, the average soil organic carbon and nitrogen contents increase from two to three times for each 10 °C decline in mean annual temperature. This temperature effect can be readily observed by noting the greater organic carbon content of well-drained surface soils as one travels from south (east Texas) to north (Minnesota) in the humid grasslands of the North American Great Plains region. Similar changes in soil organic carbon are evident as one climbs from warm lowlands to cooler highlands in mountainous regions.

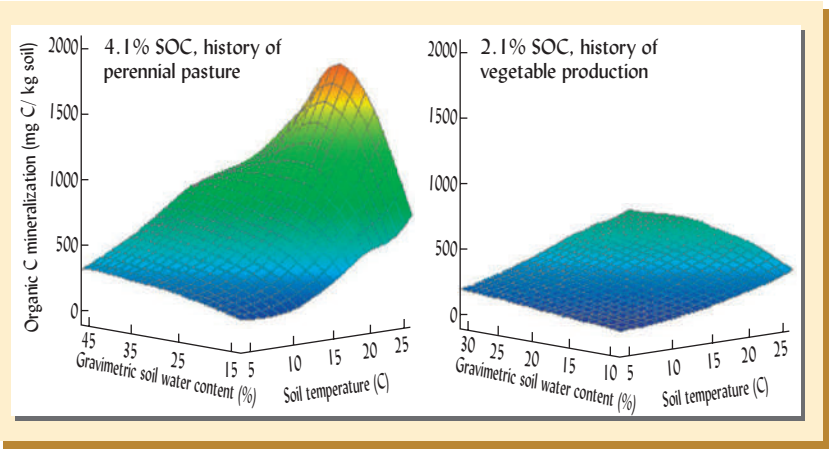

Figure 12.26 *Soil temperature and water content (horizontal axes) interact to influence organic carbon mineralization to CO_2 (vertical axis, higher rates are redder). The temperature effect was greater where labile C was high due to many years under grass pasture* (Left). *The decline in mineralization rate at high water contents in the warm pasture soil indicate that oxygen became limiting.* (Right) *The temperature effect was much smaller where labile C had been depleted by many years of high tillage, vegetable cultivation. Compared to the vegetable soil, mineralization rates in the pasture soil were almost four times as great although total SOC was only twice as great.* [Graphed from data in Curtin et al. (2012)]

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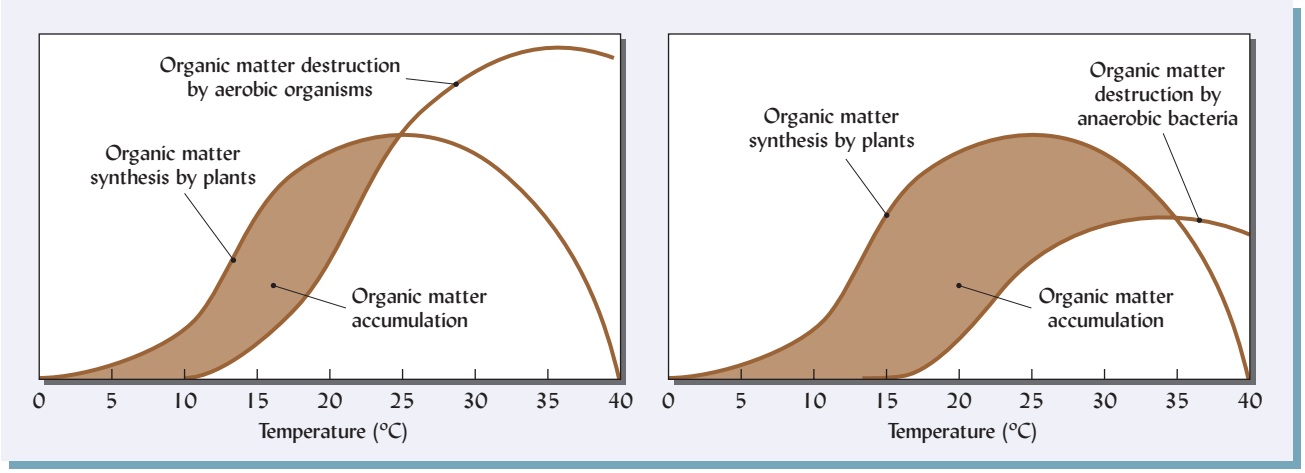

Figure 12.27 *The balance between plant production and biological oxidation of organic matter determines the effect that temperature has upon organic matter accumulation in soils. The shaded areas indicate organic matter accumulation under aerobic* (left) *and anaerobic* (right) *conditions. Soil organic matter will accumulate to higher levels in cool climates, especially in waterlogged, anaerobic soils. Note that anaerobic accumulation is greater at most temperatures and continues at higher temperatures than under aerobic conditions. This explains why a humid subtropical area such as Florida, USA, can contain both organic soils (e.g., the Everglades) and soils containing very little organic matter (e.g., in better drained parts of the state).* [Adapted from Mohr and van Baren (1954)]

Moisture. Under comparable conditions, soil organic carbon and nitrogen increase as the effective moisture becomes greater. The C/N ratio also tends to be higher in the more thoroughly leached soils of the higher rainfall areas. These relationships are evidenced by the darker and thicker A horizons encountered as one travels across the North American Great Plains region from the drier zones in the West (Colorado) to the more humid East (Illinois). The explanation lies mainly in the sparser vegetation of the drier regions. The lowest levels of soil organic matter and the greatest difficulty in maintaining those levels are found where annual mean temperature is high and rainfall is low. These relationships are extremely important to the challenge of sustainable natural resource management. It should be remembered that soil organic matter levels are not only influenced by climatic temperature and precipitation, but by a number of environmental factors, some of which in turn affect soil temperature or moisture in the soil.

Influence of Natural Vegetation

Climate and vegetation usually act together to influence the soil content of organic carbon. The greater plant productivity engendered by a well-watered environment leads to greater additions to the pool of soil organic matter. Grasslands generally dominate the subhumid and semiarid areas, while trees are dominant in humid regions. In climatic zones where the natural vegetation includes both forests and grasslands, the total organic matter is higher in soils developed under grasslands than under forests (see Figure 12.25), as explained in Section 12.7.

Effects of Texture and Drainage

While climate and natural vegetation affect soil organic matter over broad geographic areas, soil texture and drainage are often responsible for marked differences in soil organic matter within a local landscape. Under aerobic conditions, soils high in clay and silt are generally richer in organic matter than are nearby sandy soils (Figure 12.28). The finer-textured soils accumulate more organic matter for several reasons: (1) they produce more plant biomass, (2) they lose less organic matter because they are less well aerated, and (3) more of the organic material is protected from decomposition by being bound to clay surfaces (see Section 12.4) or sequestered inside soil aggregates. A given amount and type of clay can be expected to have a finite capacity to stabilize organic matter in organomineral complexes. Once this capacity

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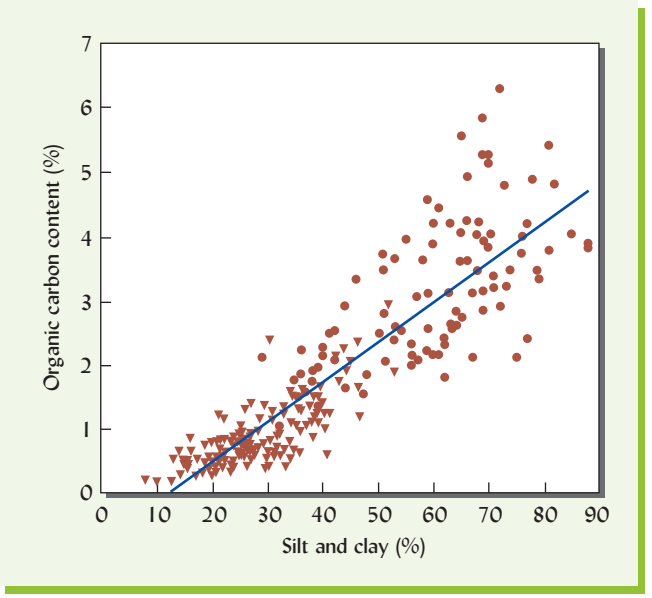

Figure 12.28 *Soils high in silt and clay tend to contain high levels of organic carbon. The data shown are for surface soils in 279 tilled maize fields in subhumid regions of Malawi (▼) and Honduras (•). All soils were moderately well to well-drained and tilled. Variability (scatter of data points) among soils with the same silt + clay content is probably due to differences in: (1) the type of clay minerals present (2:1 silicates tend to stabilize more organic carbon), (2) site elevation (cooler, high elevation locations being conducive to greater organic carbon accumulation), and (3) years since cultivation began (longer history of cultivation leading to lower organic carbon levels).* (Data courtesy of Ray R. Weil and M. A. Stine, University of Maryland, and S. K. Mughogho, University of Malawi)

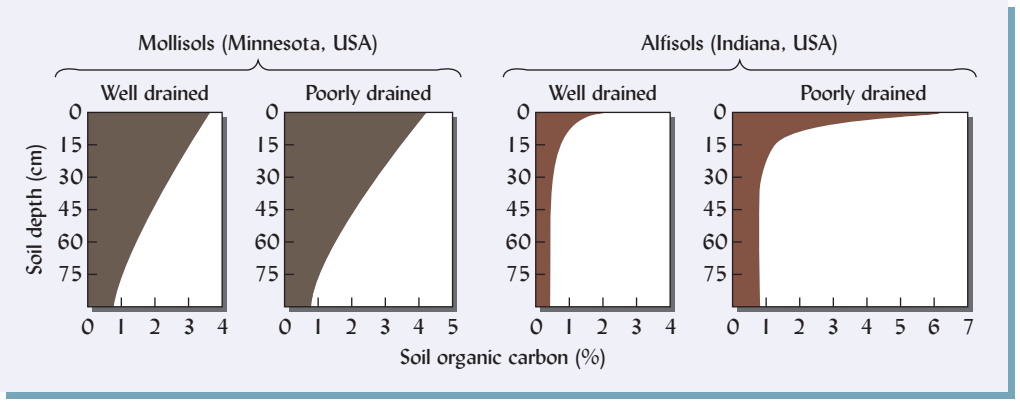

Figure 12.29 *Distribution of organic carbon in four soil profiles, two well drained and two poorly drained. Poor drainage results in higher organic carbon content, particularly in the surface horizon.* (Diagram courtesy of N. C. Brady and Ray R. Weil)

is saturated, further additions of organic matter are likely to add little to humus accumulation, as they will remain readily accessible to microbial decomposition. Thus, soil texture is thought to limit the level of organic C that can accumulate in the soil for given ecosystem.

Drainage-Aeration Effects. In poorly drained soils, the high moisture supply promotes plant dry-matter production and relatively low oxygen or even anaerobic conditions inhibit organic-matter decomposition (see Figure 12.27, *right*). Poorly drained soils therefore generally accumulate much higher levels of organic matter and nitrogen throughout their profiles than do similar but better-aerated soils (Figure 12.29).

12.9 SOIL ORGANIC MATTER MANAGEMENT

Influence of Agricultural Management and Tillage

Except where barren deserts are brought under irrigation, it is safe to generalize that cultivated land contains much lower levels of organic matter than do comparable areas under natural vegetation. This is not surprising; under natural conditions all the organic matter produced by the vegetation is returned to the soil, the vegetation is perennial with living roots present all year long, and the soil is not disturbed by tillage. By contrast, in cultivated areas

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annual plants must start each year from seed, so much of the year may be unproductive. Much of the plant material produced is removed in harvest and relatively little finds its way back to the land. Also, tillage aerates the soil and breaks up organic residues and aggregates, making the carbon more accessible to microbial decomposition.

Conversion to Cropland. A very rapid decline in soil organic matter occurs when a virgin soil is brought under cultivation. Eventually, the gains and losses of organic carbon reach a new equilibrium, and the soil organic matter content stabilizes at a much lower value (Figure 12.21). Similar declines in soil organic matter are seen when tropical rain forests are cleared; however, the losses may be even more rapid because of the higher soil temperatures involved. Declining soil organic matter is a major factor driving a downward spiral of soil degradation and poverty that plagues many of the world's 1 billion subsistence farmers (see Figure 12.30 and Section 17.1). There is some hope that efforts to introduce conservation tillage, increase plant nutrient inputs, and better manage crop residue will enable farmers to reverse this trend (see following and Section 17.6). Organic matter losses are not so dramatic if forests or prairies are converted to well-managed pasture or hay production because the latter systems still feature perennial vegetation with high root productivity and no tillage. Conversely, in many expanding urban areas, soil organic matter is increased during the years after turfgrass lawns are established on land that formerly had been depleted by crop cultivation.

Conservation Tillage. In terms of soil disturbance and the proportion of residues coverage left on the soil surface, there is a continuum of practices that range from conventional plow tillage which cause maximal disturbance and leave the soil almost bare of residue cover to no-till practices which disturb only a tiny fraction of the soil during seed placement and leave the surface nearly completely covered by residues. Practices that fall toward the low-disturbance end of the continuum include stubble mulching, some forms of chisel tillage, vertical tillage, and strip tillage. These practices along with no-till are referred to as *conservation tillage* (see Section 17.6) because they conserve soil by protecting against erosion and conserve organic carbon by discouraging the rapid decomposition of crop residues that conventional plow tillage stimulates in the surface soil. These conservation practices can therefore help maintain or restore high surface soil organic carbon levels and associated soil quality properties such as aggregate stability (Figure 12.31). As in many similar studies that compare various tillage practices to untilled or no-till systems, the effects tend to be most pronounced very near the surface.

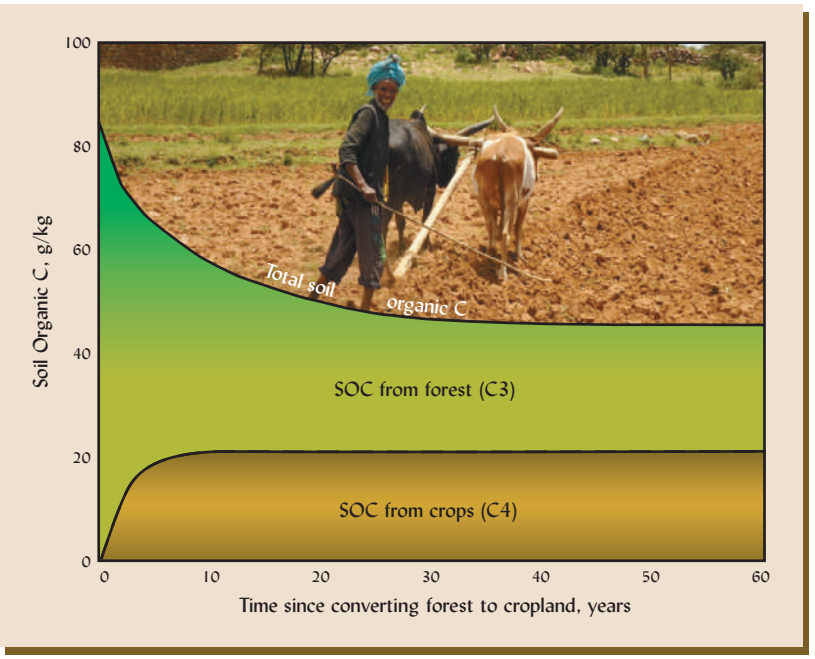

Figure 12.30 *Amounts and sources of soil organic carbon (SOC) in Ethiopian Humic Haplustands in farm fields cleared at various times in the past from native forest. The source of the SOC was determined by relative amounts of naturally occurring ^{13}C and ^{12}C isotopes. Corn and sorghum use C-4 photosynthesis, which assimilates about half as much ^{13}C as does the C-3 photosynthesis used by forest trees. Initially the forest-derived SOC declined sharply as the active pool decomposed, but leveled-off after 30 years The SOC from corn and sorghum tissues increased rapidly at first, but plateaued in only ten years, as most of this C turned over rapidly. Accumulation of SOC was thwarted by limited crop residue return (240 kg C $ha^{-1}y^{-1}$) and rapid decay, conditions typical where farmers plow excessively, produce low yields, and burn or remove crop residues. Compare the decline in total SOC to Figures 12.22 and 12.33a.* (Redrawn from Lemenih et al. (2005); photo courtesy of Ray R. Weil)

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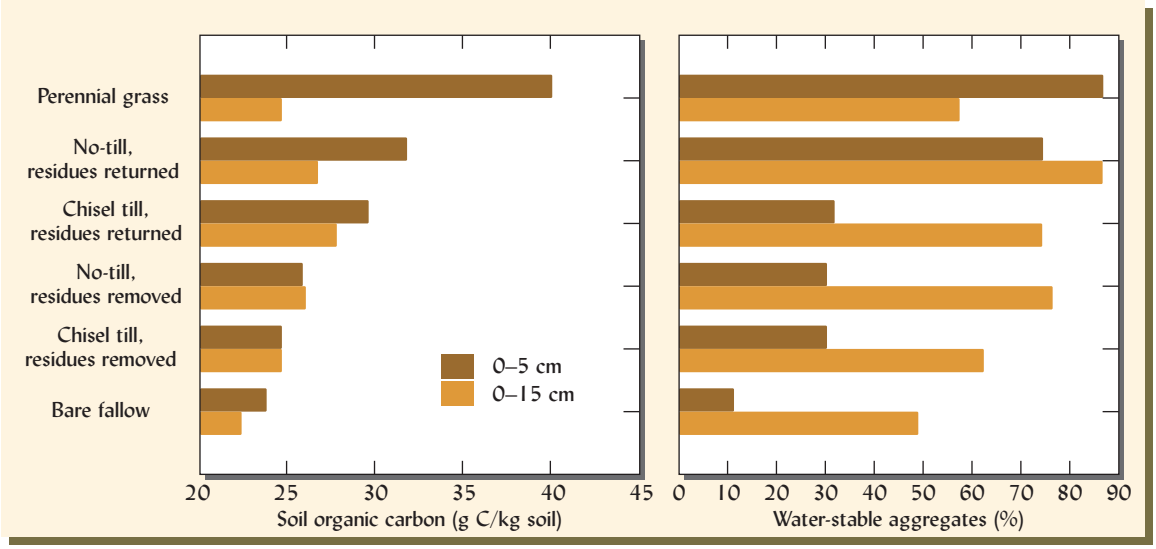

Figure 12.31 *Effects of agricultural disturbance intensity and plant residue removal on organic carbon and aggregate stability at two depths of Waukegan silt loam soil (Typic Hapludoll) from east-central Minnesota, USA. The study was designed to understand how the harvest of corn stover for cellulosic biofuel production might affect soil quality, depending on how such land was managed. Experimental treatments applied for 19 years prior to the data collection ranged from maximum positive C balance with untilled perennial grass to maximum negative balance with soil kept continuously bare. There were also several corn production systems with intermediate C balances that depended on various combinations of tillage (chisel or no-till) and residue removal (all returned or 90% removed as for biofuel feedstock).* [Graphed from data in Laird and Chang (2013)]

Influence of Rotations, Residues, and Plant Nutrients

Figure 12.32*a* illustrates changes in soil organic carbon during 140 years after the native prairie was first plowed and several different cropping systems imposed. The soils are Mollisols, and the plots can still be seen on the University of Illinois campus in the United States. These, and similar long-term experimental plots elsewhere, support the following conclusions. A complex rotation (corn, oats, and clovers) achieved higher soil organic carbon levels than monocropping (continuous corn), regardless of fertility inputs, probably because the rotation used tillage less frequently and produced more root residues. Systems that maintain soil fertility with manure, lime, and phosphorus stimulate much higher organic carbon levels, especially where a complex rotation was also followed. This result was likely related to the greater additions of organic matter in the manure and in the residues from higher-yielding crops. Application of lime and fertilizers (N, P, and K) to previously unfertilized and unmanured plots (dashed lines starting in 1955) noticeably increased soil organic matter levels, probably due to the production and return of larger amounts of crop residues and the addition of sufficient nitrogen to compliment the carbon in humus formation.

Another famous long-term experiment was begun even earlier (in 1855) at Rothamsted, England, on land that had been farmed to wheat for centuries (Figure 12.32*b*). Because the previous history of land use differed from that of the Morrow plots, the Rothamsted experiment provides lessons that are applicable to changes in old long-established agricultural systems. Because this soil was already in equilibrium with the carbon and nitrogen gains and losses characteristic of unfertilized, small-grain cropping, continued production (and harvest) of barley and wheat resulted in little change, or only a slow decline, in the already low level of soil organic carbon. Annual applications of animal manure at rates sufficient to supply all needed nitrogen resulted in a dramatic initial rise in soil organic carbon, until a new equilibrium state was approached at a much higher level. In the plots where manure was applied for only the first 20 years of the experiment, the soil organic carbon began to decline as soon as the manure applications were suspended, but the positive effect of the manure was still evident some 120 years later!

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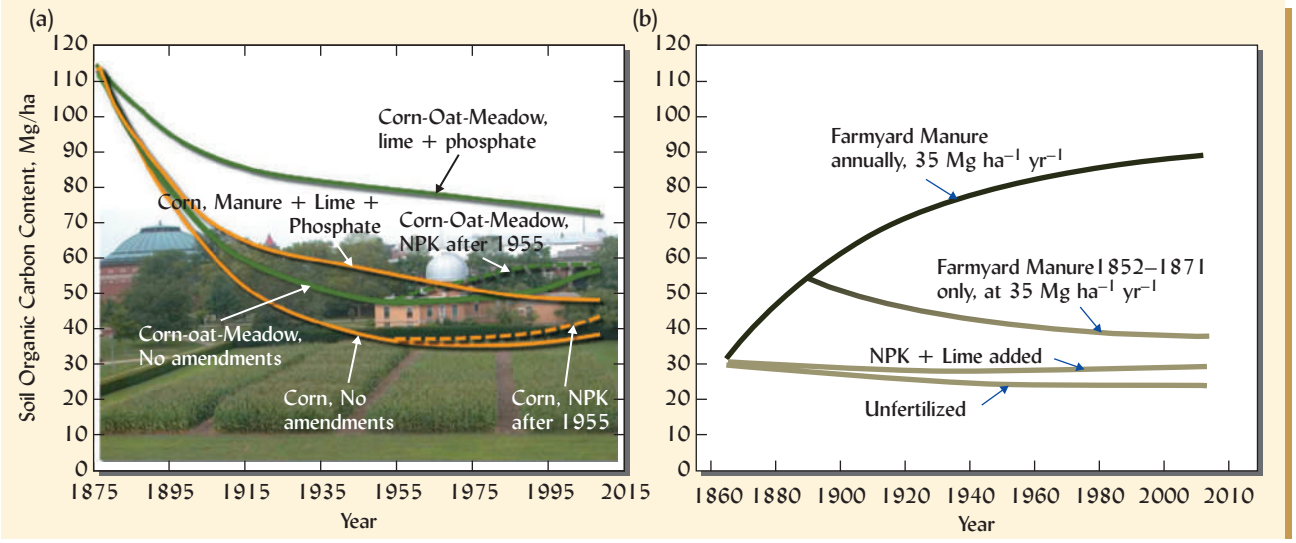

Figure 12.32 *Soil organic carbon contents of selected treatments of* (a) *the Morrow plots at the University of Illinois, USA, and* (b) *the classical Hoosfield experiment at Rothamstead Experiment Station in England. The Morrow plots were begun on virgin grassland soil in 1876 and so suffered rapid loss of organic carbon in the early years of the experiment. The Rothamstead plots were established on soils with a long history of previous cultivation. As a result, the soil at Rothamstead had reached an equilibrium level of organic carbon characteristic of the unfertilized small-grains (barley and wheat) cropping system traditionally practiced in the area. Note the large impact of farmyard manure application and the residual effect of manure some 135 years after the last application was made.* [Graphed using data recalculated from Nafziger and Dunker (2011), Jenkinson and Johnson (1977), and Johnston et al. (2009); used with permission of the Rothamstead Experiment Station, Harpenden, England. Photo courtesy of Ray R. Weil]

Results from such long-term experimental plots demonstrate that soils kept highly productive by supplemental applications of nutrients, lime, and manure and by the choice of high-yielding, diverse cropping systems are likely to have more organic matter than comparable, less productive soils. High productivity is sustainable if it involves not only greater economic harvests, but also larger amounts of roots and shoots returned to the soil.

The Conundrum of Soil Organic Matter Management

Land managers are faced with an inherent conflict between the need to *use* SOM and the need to *conserve* it. While the total carbon stabilized in the soil is important in relation to the global climate change (see Section 12.10), many beneficial effects on soil productivity and ecosystem function are realized only when the organic matter is destroyed by microbial metabolism.

In this regard, SOM is a lot like money—while it may be nice to accumulate large amounts, the benefits of having money are realized by spending it, not by keeping it "under the mattress." What is most desirable is an income large enough to allow both spending and saving. Similarly, soil management needs to simultaneously save carbon losses (by reducing losses from tillage, erosion, and aggregate disruption) while also providing a large income of preferably diverse, high-quality organic materials. Although contradictory, the goals of using and conserving must be pursued simultaneously. The *decomposition* of SOM is necessary for its use as a source of nutrients for plant and microbial growth and organic compounds that promote biological diversity, disease suppression, aggregate stability, and metal chelation. In contrast, the *accumulation* of SOM is necessary for these functions in the long term, as well as for the sequestering of C, the enhancement of soil water-holding capacity, the adsorption of exchangeable cations, the immobilization of pesticides, and the detoxification of metals.

General Guidelines for Managing Soil Organic Matter

A continuous supply of plant residues (roots and tops), animal manures, composts, and other materials must be added to the soil to maintain an appropriate level of soil organic matter,

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especially in the active pool. It is almost always preferable for the soil to be vegetated than for it to be bare for any length of time. Even if some plant parts are removed in harvest, vigorously growing plants provide below- and aboveground residues as major sources of organic matter for the soil. Moderate applications of lime and nutrients may be needed to help free plant growth from the constraints imposed by chemical toxicities and nutrient deficiencies. Where climate permits, cover crops often present a tremendous opportunity to provide protective cover and additional organic material for the soil.

There is no "ideal" amount of soil organic matter. It is generally not practical to try to maintain higher soil organic matter levels than the soil–plant–climate control mechanisms dictate. For example, 1.5% organic matter might be an excellent level for a sandy soil in a warm climate, but would be indicative of a very poor condition for a finer-textured soil in a cool climate.

Adequate nitrogen is requisite for adequate organic matter because of the relationship between nitrogen and carbon in stabilized organic matter and because of the positive effect of nitrogen on plant productivity. Accordingly, the inclusion of leguminous plants, animal manures, and the judicious use of nitrogen-containing fertilizers to enhance high plant productivity are desirable practices. Excessive nitrogen applied from mineral sources sometimes accelerates the loss of carbon in high C/N soils. Steps must also be taken to minimize the loss of nitrogen by leaching, erosion, or volatilization (see Chapter 13).

Tillage should be eliminated or limited to that needed to control weeds and to maintain adequate soil aeration. The more tillage that is performed, the faster organic matter is lost from the surface horizons and the more difficult it become to maintain high soil quality.

Perennial vegetation, especially natural ecosystems, should be encouraged and maintained wherever feasible. Improved agricultural production on existing farmlands should be pursued to allow land currently supporting natural ecosystems to be left relatively undisturbed. In addition, there should be no hesitation about taking land out of cultivation and encouraging its return to natural vegetation where such a move is appropriate. In the United States, the Conservation Reserve Program has for decades provided incentives for such action (see Section 17.14). The fact is that large areas of land under cultivation today in every continent never should have been cleared.

12.10 SOILS AND CLIMATE CHANGE[8]

Soil is a major component of the Earth's system of self-regulation that has created (and, we hope, will continue to maintain) the environmental conditions necessary for life as we know it on this planet. Biological processes occurring in soils have major long-term effects on the composition of the Earth's atmosphere, which in turn influences all living things, including those in the soil.

Global Climate Change

Of particular concern today are increases in the levels of certain gases in the Earth's atmosphere, known as **greenhouse gases**. Like the glass panes of a greenhouse, these gases allow short-wavelength solar radiation in but trap much of the outgoing long-wavelength radiation. This heat-trapping **greenhouse effect** of the atmosphere is a major determinant of global temperature and, hence, global climate change. Gases produced by biological processes, such as those occurring in the soil, account for approximately half of the rising greenhouse effect (Figure 12.33). Of the four primary greenhouse gases, only the fluorine gases (e.g., chlorofluorocarbons or CFCs) are exclusively of industrial origin.

While it is certain that the concentrations of most greenhouse gases are increasing, there is less certainty about how rapidly global temperatures are actually rising and about how these increases are likely to affect climate in different regions of the world. Predicting changes in global temperature is complicated by numerous factors, such as cloud cover and volcanic dust,

[8]For a review of the potential for soil management to mitigate climate changes, see Paustian and Babcock (2004) , Mackey et al. (2013) and Lal (2015).

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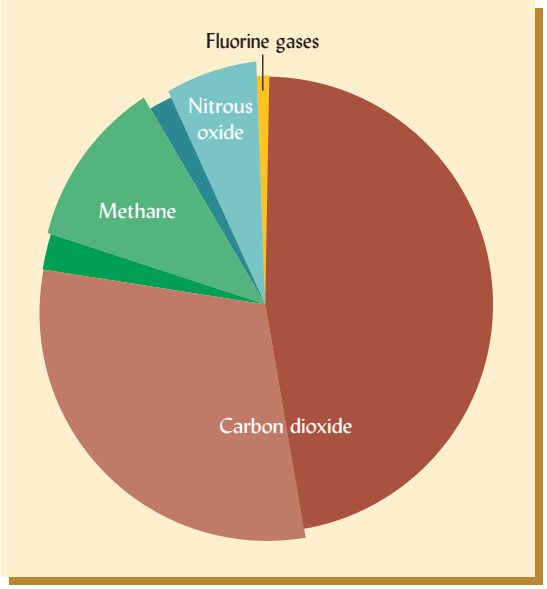

Figure 12.33 *Relative contribution of different gases to the global warming that is driving climate change. The lighter-shaded portions indicate the emissions related to biological systems (in which soils play a role), the darker portions being industrial contributions.* [Based on data in USEPA (2011)]

which can counteract the heat-trapping effects of the greenhouse gases. However, most scientists believe that the average global temperature has increased by approximately 1.0 °C during the past century, and predict that it is likely to increase by another 2–4 °C in this century. If this increase in fact takes place, major changes in the Earth's climate are sure to result, including changes in rainfall distribution and growing season length, increases in sea level, and greater frequency and severity of storms and droughts. The rise in sea level alone, as predicted by some climate models, would threaten the homes of hundreds of millions of people living in coastal areas, mainly in Asia and North America. Through national programs and international agreements much effort and expense are currently being directed at reducing the anthropogenic (human-caused) contributions to climate change. Soil science has the potential to contribute greatly to our ability to deal with climate change and mitigate the levels of greenhouse gases.

Carbon Dioxide

In 2013, the atmosphere contained about 400 ppm CO_2, as compared to about 280 ppm before the Industrial Revolution. Levels are increasing at about 0.5% per year. Although the burning of fossil fuels is a major contributor, much of the increase in atmospheric CO_2 levels has come from a net loss of organic matter from the world's soils. Through aerobic decomposition, the carbon in plant biomass and soil organic matter—carbon that originated from CO_2 in the atmosphere—is eventually converted back into CO_2 and returned to the atmosphere. Box 12.1 illustrated the importance of soil organic matter in regulating atmospheric CO_2 levels. Research (e.g., Figure 12.34) indicates that the feedback between the soil and atmosphere works both ways—changes in the levels of gases beneficial or harmful to plants influence the rate at which carbon accumulates in soil organic matter.

We have already discussed many ways that land managers can increase levels of soil organic matter (Section 12.8) by changing the balance between gains and losses. Gains in soil organic matter occur first in the active fractions, but eventually some of the carbon moves into the stable passive fraction, where it may be *sequestered* for hundreds or thousands of years. The opportunities for sequestering carbon are greatest for degraded soils that currently contain only a small portion of the organic matter levels they contained originally under natural conditions. Reforestation of denuded areas is one such opportunity. Conversion of cultivated land to perennial vegetation may sequester carbon at twice these rates.

Hundreds of studies have shown that reducing or eliminating tillage generally enhances soil quality and surface soil carbon levels. On average, switching the management of cropland

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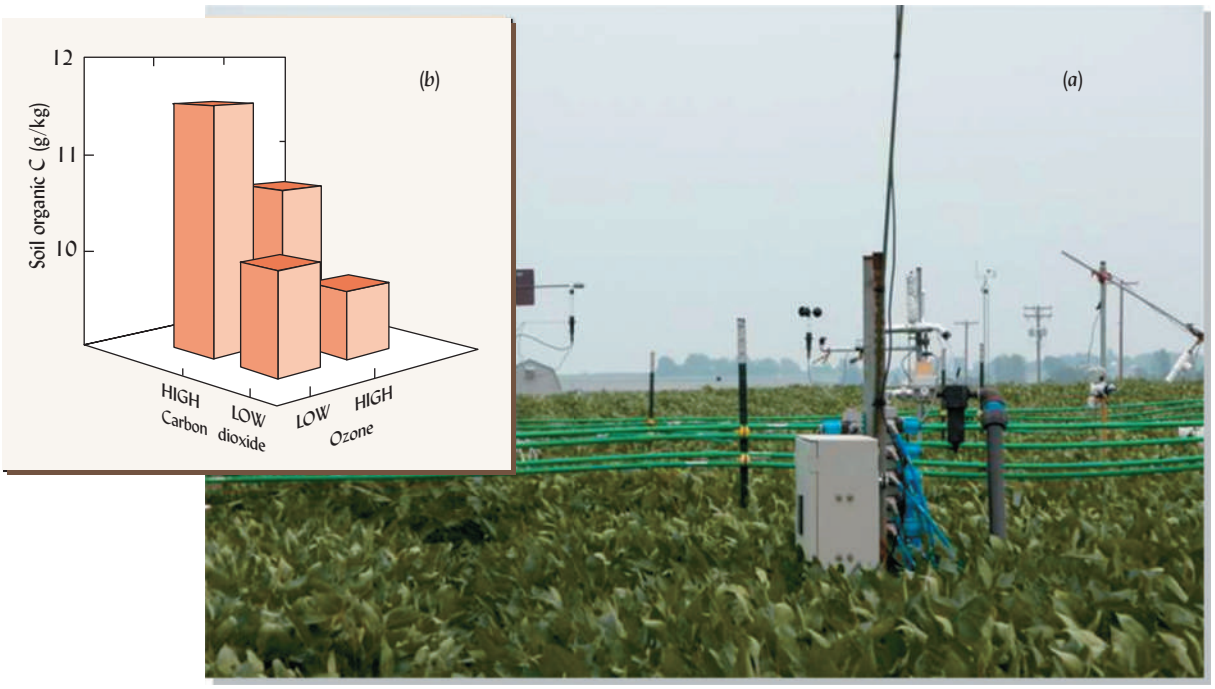

Figure 12.34 *Changing atmospheric composition affects the C cycle.* (a) *Within a circular FACE (free air carbon enrichment) experimental plot on Mollisols at the University of Illinois, USA, soybeans experience air altered to simulate the atmospheric composition expected in 50 years. Horizontal tubing and vertical poles supply computer-controlled concentrations of carbon dioxide and/or ozone, which are continuously monitored by various sensors. Increasing atmospheric CO_2 from low (350 mg/L, the ambient level) to high (500 mg/L, the level expected by the year 2050) enhanced photosynthesis and plant growth, thus increasing the amount of fixed carbon available for translocation to the roots and eventually to the soil.* (b) *Data from a different carbon–ozone enrichment experiment on Ultisols in Maryland, USA, show measurably increased soil organic carbon after five years of soybean and wheat crops grown in high CO_2 air. Increased root:shoot ratio, rhizodeposition of carbon compounds, and overall greater litter inputs all played a role. Ozone, a pollutant at ground level, injures plants, reduces photosynthesis, and therefore impacts the soil in a manner opposite to that of CO_2. The data suggest the full effect of CO_2 is seen only when ozone remains at low levels.* [Data from Weil et al. (2000); photo courtesy of Ray R. Weil]

from conventional plow tillage to no-tillage appears to sequester 0.2–0.5 Mg/ha of carbon in the surface soil annually during the first 10–20 years until a new, higher equilibrium carbon level is reached. Highest rates of C sequestration are likely where an integrated conservation farming system is used that combines minimization of tillage disturbance with diverse crop rotations and cover crops, integrated fertility management, and retention of plant residues on the soil surface. However, most of the data we have on the effect of tillage practices are based on sampling just the upper 5–20 cm of soil. The few studies that have analyzed soil down to 1 m tend to question whether, by itself, no-till management of annual row crops significantly increases carbon stored in soils per unit of land area when the entire soil profile depth is considered (Figure 12.35).

By slowly increasing soil organic matter to near precultivation levels, improved soil management could significantly enhance society's efforts to stem the rise in atmospheric CO_2 and at the same time improve soil quality and plant productivity. Some estimates suggest that during a 50-year period, improved management of agricultural lands could provide about 15 to 25% of the CO_2 emission reductions that need to be made. It should be noted, however, that in accordance with the factors discussed in Section 12.9, soils have only a finite capacity to assimilate carbon into stable soil organic matter. Therefore carbon sequestration in soils can only buy time while other kinds of actions (shifts to renewable energy sources, increased fuel efficiency, etc.) are fully implemented to reduce carbon emissions to levels that will not threaten climate stability.

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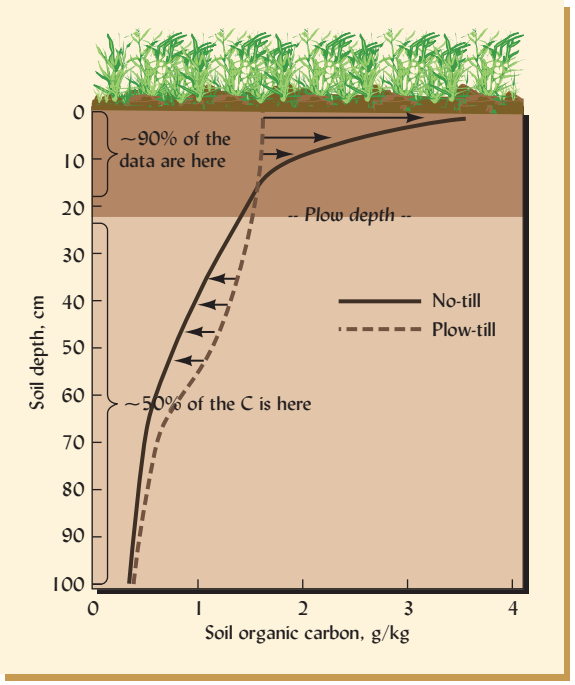

Figure 12.35 *Representative trends showing that conversion of plow-tilled cropland to no-till management encourages the accumulation of high levels of SOC in the surface few cm of soil, stimulating aggregation, high infiltration, and resistance to erosion. Most research on the impact of tillage on SOC has studied only the upper 10–25 cm of soil. However, some of the small number of studies that sampled much greater depths suggest that, in the subsoil, plowed soils may accumulate more SOC than under no-till, possibly due to differences in crop rooting depth between tillage systems. Therefore it is uncertain what the effect of no-till may be in the overall carbon storage in the soil.* (Based on many sources, diagram courtesy of Ray R. Weil)

Biofuels Production. Soils are deeply involved with *biofuels*, both because good soils will be needed to grow the plant biomass feedstocks and also because removal of this plant material can greatly alter the C balance in soils. Biofuels from plant material make attractive substitutes for gasoline and diesel because, in theory, they are both renewable and carbon neutral (the CO_2 emitted into the atmosphere when they are used is taken back out of the atmosphere to produce more biofuel feedstock). Biodiesel consists of fuel-grade oil extracted from the same crops (e.g., soybeans, rapeseed, and sunflower) used to provide cooking oil. Ethanol has long been made by fermenting sugar from sugarcane or starch from corn grain (much like making whiskey), but this process competes with food and feed uses of the sugar and starch and, in the case of corn, is generally inefficient. Instead, attention is turning toward the production of ethanol from cellulosic residues such as corn stover (the stalks and leaves) and switchgrass, which can be grown much more cheaply and abundantly than grain.

Much controversy still surrounds the question as to whether such fuels will actually produce more energy than is consumed in the fossil fuel used to grow and process the crop. However, one aspect that should *not* be controversial is the critical importance of leaving enough crop residues on the soil to maintain the levels of soil organic matter consistent with high quality and continued productivity of the soil resource. Recent research suggests that soil organic matter levels, aggregate stability, and other soil properties critical to sustaining productivity may rapidly suffer if all, or even half, of the corn stover is removed to make biofuels (Table 12.6). Unfortunately, the need to "share" the plant residues with the soil has not always been recognized by energy engineers and planners advising policy makers on biofuel production strategies. Some have advised not only that all aboveground residues be harvested to make the biofuels, but that the crops be genetically altered to reduce the ratio of roots to shoots—just the opposite of what sustainable soil management requires!

Wetland Soils. Discussion up to this point has focused on organic matter in mineral soils. Under waterlogged conditions in bogs and marshes, the oxidation of plant residues is so retarded that the soils in these environments consist mainly of organic matter and many are classified as Histosols in *Soil Taxonomy* (see Chapter 3). Although they cover only about 2% of the world's land area, Histosols (and Histels—permafrost soils with organic surface horizons) are important in the global carbon cycle because they hold a large proportion of global soil carbon. Drainage of these soils for high-value horticultural production speeds the oxidation of

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Table 12.6
DETERIORATION OF SOIL ORGANIC CARBON AND STRUCTURAL PROPERTIES IN THE UPPER 5–10 CM OF THREE OHIO SOILS AFTER ONE YEAR OF CORN STOVER REMOVAL FOR BIOFUEL PRODUCTION[a]

Soil series, great group	Cropping history	Stover returned, Mg/ha[b]	Soil organic C, g/kg	Soil bulk density, Mg/m^3	Tensile strength of soil aggregates, kPa	Water stable aggregates < 4.75 mm diameter, %
Rayne silt loam (Hapludults)	33-yr continuous no-till corn	5	29	1.46	140	18
		0	19	1.50	50	13
Hoytville clay loam (Epiaqualfs)	8-yr corn/soybean minimum till	5	26	1.31	380	20
		0	22	1.49	120	8
Celina silt loam (Hapludalfs)	15-yr corn/ soybean no-till	5	28	1.25	225	36
		0	21	1.42	80	13

[a]Data selected from Blanco-Canqui et al. (2006).
[b]5 Mg/ha corn stover represented the normal practice of returning all aboveground residues after corn grain harvest. Return of 0 Mg/ha represented removal of all stover for biofuel production.

organic matter, which over time destroys the soil itself. Draining Histosols, or mining them for peat (Box 12.5), can make major contributions to the rise in atmospheric CO_2. On the other hand, rising sea levels associated with global warming may lead to more Histosol formation, which in turn may buffer climate change by sequestering more CO_2. Although storms increasingly destroy coastal marshes, the rising sea level will flood more coastal land area, creating conditions conducive to the formation of more Histosols in tidal marshes and mangrove forests along tropical coasts (Figure 12.36). The organic matter accumulation in these newly formed Histosols would represent a significant sequestering of CO_2 that might help to buffer the global warming trend (as would the increased absorption of CO_2 by the greater volume of ocean waters). However, such predictions are complicated by the involvement of another greenhouse gas, methane, which is emitted by some Histosols and other wetland soils.

Methane. Methane (CH_4) occurs in the atmosphere in far smaller amounts than CO_2. However, methane's contribution to the greenhouse effect is nearly half as great as that from CO_2 because each molecule of CH_4 is about 25–30 times as effective as CO_2 in trapping outgoing radiation. The level of CH_4 is rising at about 0.6% per year. In 2015, there was about 1.85 ppm CH_4 in the atmosphere, more than double the preindustrial level. Soils serve as both a source and a sink for CH_4—that is, they both add CH_4 and remove it from the atmosphere.

Biological soil processes account for much of the methane emitted into the atmosphere. When soils are strongly anaerobic, as in wetlands and rice paddies, bacteria produce CH_4, rather than CO_2, as they decompose organic matter (see Sections 7.4 and 12.2). Among the factors influencing the amount of CH_4 released to the atmosphere from wet soils are: (1) the maintenance of a redox potential (Eh) near 0 mV, (2) the availability of easily oxidizable carbon, either in the soil organic matter or in plant residues returned to the soil, and (3) the nature and management of the plants growing on these soils (70–80% of the CH_4 released from flooded soils escapes to the atmosphere through the hollow stems of wetland plants). Figure 12.37 shows how these factors can influence CH_4 emissions from flooded rice paddies. Although not part of the study illustrated here, it has been demonstrated that periodically draining rice paddies prevents the development of extremely anaerobic conditions and therefore can substantially decrease CH_4 emissions. Such management practices

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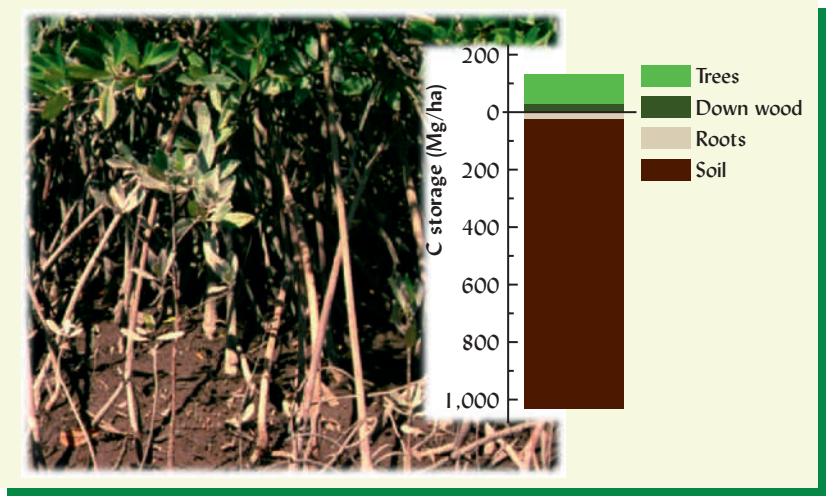

Figure 12.36 *A tropical mangrove ecosystem, like most forest ecosystems, stored most of its C in the soil rather than in the vegetation. This, combined with wetland condition conductive to high levels of soil C storage, explains why tropical mangrove forests contain such large soil C stocks per unit area.* [Photo courtesy of Ray R. Weil; graphed from supplementary data in Donato et al. (2011)]

should be given serious consideration, as rice paddies are thought to be responsible for up to 25% of global CH_4 production.

Salt marshes (such as found along coastal areas) tend to emit much less methane than do freshwater swamps, therefore the balance of greenhouse gases entering and leaving coastal marshes is likely to be more favorable for mitigating global warming. Sulfate-reducing microbes derive much more energy by using sulfate as their alternative electron acceptor than methanogens can derive by reducing carbon dioxide to methane. Therefore, the high levels of sulfate in seawater allow sulfate-reducing prokaryotes to outcompete the methanogens for available carbon substrates in salt marshes. The large amount of sulfate reduction also tends to *poise* the redox potential, preventing it from falling quite low enough to favor methane production (see Section 7.3).

Wetland soils are not the only ones that contribute to atmospheric CH_4. Significant quantities of methane are also produced by the anaerobic decomposition of cellulose in the guts of termites living in well-aerated soils (see Section 11.5), and of garbage buried deep in landfills (see Section 18.10).

In well-aerated soils, certain **methanotrophic bacteria** produce the enzyme *methane monooxygenase*, which allows them to oxidize methane as an energy source:

$$\underset{\text{Methane}}{CH_4} + {}^{1}\!/_{2}O_2 \longrightarrow \underset{\text{Methanol}}{CH_3OH} \qquad (12.5)$$

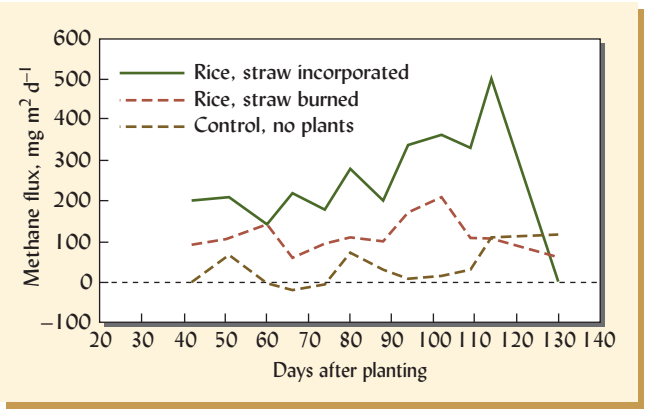

Figure 12.37 *Factors affecting the emission of methane, a very active greenhouse gas, from a flooded rice paddy soil in California, USA. The methane is generated by microbial metabolism in the soil and transported to the atmosphere through the rice plant. Emissions were greatest during the period of most active rice growth in mid-season. The sharp increase in methane near the end of the season was due to a rapid release of accumulated methane as the soil dried down and cracks opened up in the swelling clay. Very little methane was released if no rice was planted. Moderate amounts were released if rice was planted but rice residues from the previous crop had been burned off. The highest amounts of methane were released where rice was planted and the straw from the previous crop had been incorporated into the soil. Once the soil was drained at the end of the season, no more methane was produced.* [Redrawn from Redeker et al. (2000), with permission of the American Association for the Advancement of Science]

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BOX 12.5

PEAT FOR POTS AND POWER: *UN*SUSTAINABLE SOIL MINING[a]

The peat you may have purchased in large bags at the garden center was probably produced by literally mining wetland soils. More than half of the world's wetlands are considered to be *peatlands*, deep Histosols that occur mainly in cool climates (especially in Canada) and contain layers of *woody*, *sedimentary*, and *fibrous peat*. The fibrous peat is most desirable for horticultural uses such as mulching flower beds and topdressing or amending turf-grass, especially in sand-based golf greens (see Section 12.7). Most containerized plants are grown in soilless media consisting largely of peat. Peat and similar organic materials are lightweight, have great water-holding capacity (10–20 times their dry weight), contribute considerable cation exchange capacity for holding available plant nutrients, and provide large pores to promote drainage and aeration.

With the phenomenal growth in demand by horticultural industries, mining of Canadian Histosols for peat is increasing. This activity increases greenhouse gas emissions for two reasons. First, mining destroys the wetlands and eliminates their C sequestration function. Second, peat used for horticultural applications eventually decomposes, and its carbon is returned to the atmosphere. Even if peatland restoration efforts are successful and the cutover peatlands are restored to their role as net carbon sinks, research estimates it would take 2000 years to sequester the C lost during the past 50 years.

An even more direct conversion of sequestered C in peat to CO_2 is the extensive use of peat for fuel. In Scotland and Ireland, rural people still cut peat blocks from bog soils and dry them for use in home heating (Figure 12.38). In Russia, peat is mined on a much larger scale to provide fuel for electricity generation. While such peat utilization may be profitable in the short term, it is an inherently destructive and unsustainable use of the Histosol resource. It is also incompatible with global efforts to slow climate change by reducing CO_2 emissions.

Alternatives do exist. Organic wastes stabilized by composting can be used in place of peat for potting mixes and in turfgrass amendments. Composted materials provide most of the same benefits as peat, but, in addition, they may also suppress plant diseases (Section 11.13) and release significant levels of nutrients as they slowly decompose. Use of compost made from sewage sludge, farm manure, or municipal garbage not only provides a low-cost, renewable, greenhouse-neutral organic material for horticulture, it also solves some vexing waste disposal problems. Biochar (see Section 20.9) made from crop residues or wood wastes may be another potential substitute for peat. With the mining of large quantities of peat continuing, the shift to such alternative materials needs to be encouraged.

Figure 12.38 *Peat blocks cut from the Histosol profile (see trench) are stacked to dry so they can be burned to heat rural homes in western Scotland.* (Photo courtesy of Josh Weil)

[a] Carlile, et al. (2015) discusses practical and sustainable alternatives to peat for organic growing media.

This reaction, which is largely carried out in soils, reduces the global greenhouse gas burden by about 1 billion Mg of methane annually. Unfortunately, the long-term use of inorganic (especially ammonium) nitrogen fertilizer on cropland, pastures, and forests has been shown to reduce the capacity of the soil to oxidize methane (see also Section 13.14). The evidence suggests that the rapid availability of ammonium from fertilizer stimulates ammonium-oxidizing bacteria at the expense of the methane-oxidizing bacteria. Long-term experiments in Germany, Belgium, and England indicate that supplying nitrogen in organic form (as compost or manure) actually enhances the soil's capacity for methane oxidation (Figure 12.39).

Nitrous Oxide. Nitrous oxide (N_2O) is another greenhouse gas—one with even more global warming power than methane. The impact of this gas is some 300 times greater than that of an equal mass of carbon dioxide. About 75% of nitrous oxide emissions in the United States originate in soils (including manure destined for soil application). It is

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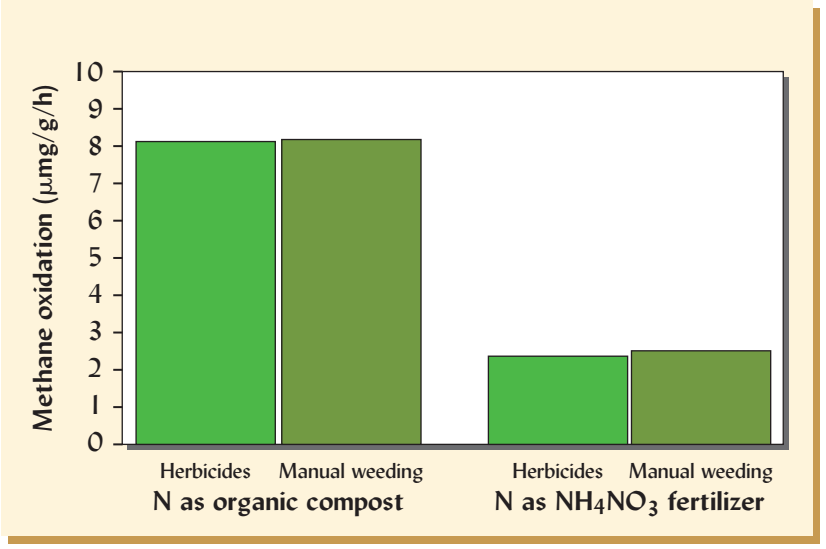

Figure 12.39 *Effect of agricultural soil management on methane oxidation rates in a sandy loam soil in Belgium. The data are from samples taken in June of the third year of an experiment comparing monocropped corn grown with and without synthetic agrochemicals. Using herbicides (light green) as compared to manual weeding (dark green) had no effect. On the other hand, as in other experiments around the world, the methane oxidation capacity of the soil was dramatically reduced by the use of inorganic N fertilizer as compared to an organic source of N (compost in this case).* [Data selected from Seghers et al. (2005)]

produced by microorganisms under low oxygen conditions—such as in poorly aerated soils or in the interior of organic nitrogen-rich soil aggregates (Section 7.5). Its production by soil prokaryotes requires a ready supply of energy, usually from easily decomposed carbon. Emissions of this greenhouse are often associated with a combination in time and space of highly fertile soil conditions, with warm summer temperatures and excessive wetness. Since nitrous oxide is a component of the nitrogen cycle, it will be further discussed in the next chapter (see Section 13.9).

Because the soil can act as a major source or sink for carbon dioxide, methane, and nitrous oxide, it is clear that, together with steps to modify industrial and transportation section outputs of these gases, soil management has a major role to play in controlling the atmospheric levels of greenhouse gases. Figure 12.40 puts into perspective the relative potential of the main agricultural soil-related strategies to mitigate climate change. The mitigation potential is shown as CO_2 equivalent climate forcing so that effects on emissions of the three greenhouse gases can be fairly compared and summed together. It is clear that among the many strategies, sequestering more carbon into soils under croplands and grazing lands and restoring formerly drained wetlands are the three most important. Fortunately, these measures are quite feasible as their implementation would not only reduce greenhouse gases, but also improve soil quality and provide the benefits of enhanced soil function and productivity to land owners.

12.11 COMPOSTS AND COMPOSTING

Composting is the practice of creating partially stabilized, useful organic decay products outside of the soil by mixing, piling, or otherwise storing organic materials under conditions conducive to aerobic decomposition and nutrient conservation (Figure 12.41). The decomposition processes and organisms involved are only somewhat similar to those already described for the formation of humus in soils. Important differences include the fact that with composting, decay occurs outside of the soil and commonly undergoes periods of high temperatures not found in soils. Also, in compost there is little opportunity for sorption onto clay or occlusion inside aggregates. The finished product, **compost**, is popular as a mulching material, as an ingredient for potting mixes, as an organic soil conditioner, and as a slow-release fertilizer.

High-quality compost can be made at ambient temperatures by a slow decomposition process, or more quickly by a process called ***vermicomposting***, in which certain litter-dwelling (epigeic) earthworms are added to help transform the material. Vermicompost essentially consists of the casts made by earthworms eating the raw organic materials in moist, aerated piles. The piles are kept shallow to avoid heat buildup that could kill the worms.

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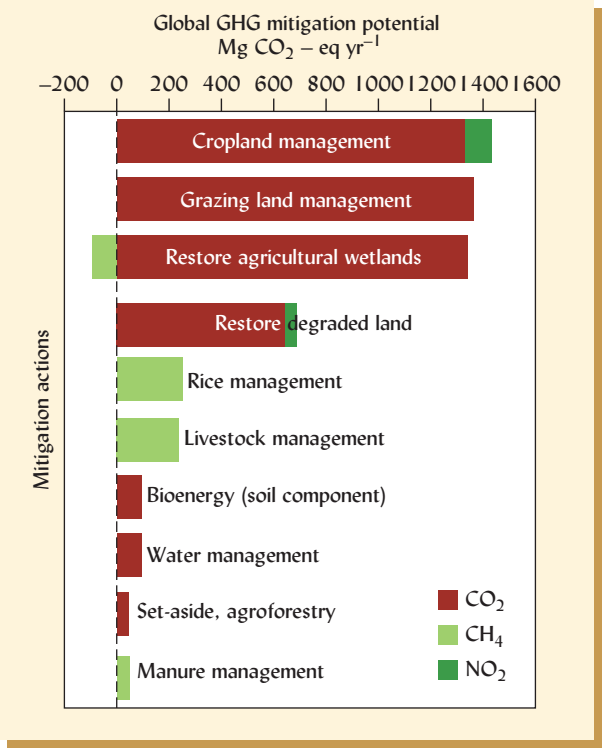

Figure 12.40 *Relative global warming mitigation potential of the main low-carbon agricultural strategies to mitigate climate change. To account for the much higher heat absorption capacity of methane and nitrous oxide compared to carbon dioxide, the mitigation potential is shown as Mg of CO_2 equivalent reduced per year. It is clear that among the many strategies, sequestering more carbon into soils under croplands and grazing lands, as well as restoring drained wetlands, are the three most important.* [Graph adapted from Norse (2012)]

Figure 12.41 *A special machine turns large-scale compost windrows (direction of travel is away from the photographer) to mix the material and maintain well-aerated conditions at a facility in North Carolina, USA, where university dining hall food scraps are processed into compost for campus landscaping.* (Photo courtesy of Ray R. Weil)

We will focus, however, on the most commonly practiced type of composting, in which intense decomposition activity occurs within large, well-aerated piles. This approach is called ***thermophilic composting*** because the large mass of rapidly decomposing material, combined with the insulating properties of the pile, results in a considerable buildup of heat.

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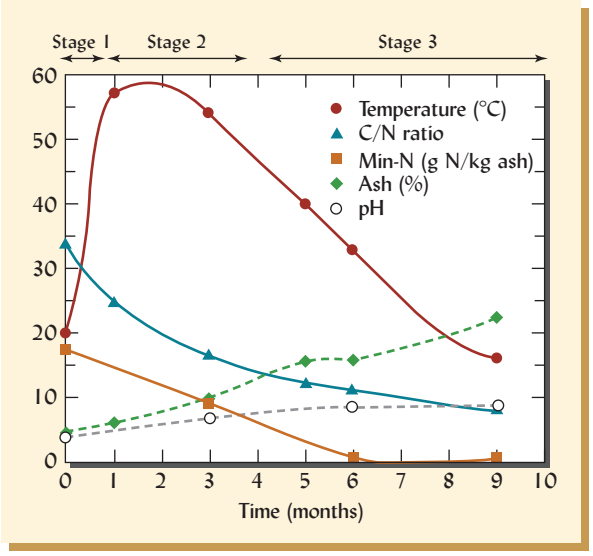

Figure 12.42 *Physical and chemical changes during the composting process. In this case, easily decomposable plant materials were composted in a covered structure and turned monthly. This resulted in a very rapid rise in temperature in stage 1, temperatures maintained above 40 °C for a long thermophilic stage 2, until the readily decomposed compounds were depleted and temperatures dropped to the mesophilic range again during curing (stage 3). Because 83% of the initial C but only 28% of the initial N was lost as gases, the C/N ratio declined from about 35 in the initial material to 9 in the finished compost. Most of the elements other than C and O were conserved, resulting in an increasing ash content (shown as a percentage of the dry weight). Mineral-N ($NH_4^+ + NO_3^-$), shown here as proportion of the ash, was high in the initial material, but declined to near zero as composting proceeded and the N was assimilated into microbial biomass and synthesized organic compounds. The pH of the material increased from 4 to 8 as organic acids were decomposed.* [Graphed from data in Lynch et al. (2006)]

Composting Process. Thermophilic compost typically undergoes a three-stage process of decomposition (Figure 12.42): (1) During a brief, initial ***mesophilic*** stage, sugars and readily available microbial food sources are rapidly metabolized, causing the temperature in the compost pile to gradually rise from ambient levels to over 40 °C. (2) A *thermophilic* stage occurs during the next few weeks or months, during which temperatures rise to 50–75 °C while oxygen-using thermophilic organisms decompose cellulose and other more resistant materials. Frequent mixing during this stage is essential to maintain oxygen supplies and assure even heating of all the material. The easily decomposed compounds are used up, and humuslike compounds are formed during this stage. (3) A second mesophilic or *curing stage* follows for several weeks to months, during which the temperature falls back to near ambient, and the material is recolonized by mesophilic organisms, including certain beneficial microorganisms that produce plant-growth-stimulating compounds or are antagonistic to plant pathogenic fungi (see Section 11.14).

Nature of the Compost Produced. As raw organic materials are decomposed in a compost pile, the content of simple plant molecules like sugars and cellulose declines, and the content of lower energy, complex molecules increases markedly. During the composting process, the C/N ratio of organic materials in the pile decreases until a fairly stable ratio, in the range of 10:1–20:1, is achieved (Figure 12.42). The CEC of the organic matter may increase to about 50–70 $cmol_c$/kg of compost.

Although 50–75% of the carbon in the initial material is typically lost during composting, mineral nutrients are mostly conserved. The proportion that is mineral content (referred to as *ash* content) therefore increases over time, making finished compost more concentrated in nutrients than the initial combination of raw materials used. Properly finished compost should be free of viable weed seeds and pathogenic organisms, as these are generally destroyed during the thermophilic phase. However, inorganic contaminants such as heavy metals are *not* destroyed by composting. Proper management of compost is essential if the finished product is to be desirable for use as a potting media or soil amendment (see Box 12.6).

Benefits of Composting. Although making compost may involve more work and expense than applying uncomposted organic materials directly to the soil, the process offers several distinct advantages: (1) Composting provides a means of safely storing organic materials with a minimum of odor release until it is convenient to apply them to soils. (2) Compost is easier to handle than the raw materials as a result of the 30–60% smaller volume and greater uniformity of the resulting material. (3) For residues with a high initial C/N ratio, proper

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BOX 12.6

MANAGEMENT OF A COMPOST PILE

Materials to Use. Materials good for home composting include tree leaves (best if shredded), grass clippings, weeds (best before going to seed), kitchen scraps, wood shavings, gutter cleanings, pine needles, spoiled hay, straw, and even vacuum cleaner dust. Large-scale commercial compost is often made from materials such as municipal garbage, sewage sludge, wood chips, animal manures, municipal leaves, and food-processing wastes.

Materials to Avoid. Some materials to avoid include meat scraps (odors, rodents), cat droppings (carry microbes harmful to infants and pregnant women), sawdust from pressure-treated lumber and plywood (heavy metals and arsenic), and plastics and glass (nonbiodegradable; nuisance or dangerous in final product).

Balancing Nutrients. Although highly carbonaceous materials can be made to compost satisfactorily if they are turned frequently and kept moist, best results are obtained if high-C/N-ratio materials (e.g., brown leaves, straw, or paper) are mixed with low-C/N-ratio materials (e.g., green grass clippings, legume hay, blood meal, sewage sludge, or livestock manure) so as to achieve an overall C/N ratio between 20 and 30. Nitrogen fertilizer can also be added to lower the C/N ratio.

Other materials commonly added to improve nutrient balance and content include mixed fertilizers (N, P, and K), wood ashes (K, Ca, and Mg), bone meal or phosphate rock powder (P and Ca), and seaweed (K, Mg, Ca, S, and micronutrients). Some of these materials contain enough soluble salts to necessitate leaching of the finished compost before using it on salt-sensitive plants.

Composting Methods. Provide good aeration throughout the pile, but build the pile large enough to provide mass sufficient to generate heat and prevent excessive drying. Backyard compost piles should be at least 1 m square and 1 m high. Compost bins are available to make turning the compost easier. Large-scale composting is usually carried out in windrows, about 2–3 m wide, 1–2 m tall, and many meters long (Figure 12.43*b*). In dry climates, compost may be made in pits dug about 1 m deep to protect the material from drying. The various materials to be composted can be mixed together or applied in thin layers. Often, a small amount of garden soil or finished compost is added to ensure that plenty of decomposer organisms will be immediately available. Compost activators containing microbial inoculum or herbal extracts are available, but while some may speed the initial heating of the pile, scientific tests rarely show any other advantage to using these preparations.

Oxygen and Moisture Control. Low oxygen levels, usually due to inadequate turning combined with excessive moisture, can produce putrid odors as anaerobic decomposition takes over. Monitoring temperature and oxygen levels in the pile can help avoid this situation. To promote good aeration it is best to mix in a bulking agent such as wood chips, avoid excessive packing, and either turn the pile or pull a stream of air through it (Figure 12.43). If turning is used, this should be done during the thermophilic stage whenever the temperature begins to drop. The compost water content should be maintained at 50–70%. Properly moist compost will feel damp—but not dripping wet—when squeezed. Turning the pile during dry weather can help reduce excess moisture, while turning it during rain can help moisten a too-dry pile.

Figure 12.43 (a) *An efficient and easily managed method of composting suitable for homeowners is the three-bin method in which materials are turned with a pitchfork from one bin to the next. The perforated white plastic pipes enhance aeration. The leftmost bin contains relatively fresh materials, while the one at the right contains finished compost.* (b) *Sewage sludge mixed with wood chips is composted by a static (unturned), aerated pile method in which air is drawn through the large compost windrow via perforated pipes and small blowers. The air is expelled through smaller piles of finished compost, which absorb any odors.* (Photos courtesy of Ray R. Weil)

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composting ensures that any nitrate depression period (see Figure 12.8) will occur in the compost pile, not in the soil, thereby avoiding induced plant nitrogen deficiency. (4) When applied to the soil, composted materials generally decompose and mineralize much more slowly than uncomposted organic materials. (5) **Co-composting** low-C/N-ratio materials (such as livestock manure and sewage sludge) with high-C/N-ratio materials (such as sawdust, wood chips, senescent tree leaves, or municipal solid waste) provides sufficient carbon for microbes to immobilize the excess nitrogen and minimize any nitrate leaching hazard (see Section 13.8) from the low-C/N materials. It also provides sufficient nitrogen to speed the decomposition of the high-C/N materials. (6) High temperatures during the thermophilic stage in well-managed compost piles kill most weed seeds and pathogenic organisms in a matter of a few days. Under less ideal conditions, temperatures in parts of the pile may not exceed 40–50 °C, so weeks or months may be required to achieve the same results. (7) Most toxic compounds that may be in organic wastes (pesticides, natural phytotoxic chemicals, etc.) are destroyed by the time the compost is mature and ready to use. Composting is even used as a method of biological treatment of polluted soils and wastes (see Section 18.5). (8) Some composts contain microorganisms that can effectively suppress soilborne plant diseases (see Section 11.13). Most success in disease suppression has occurred when well-cured compost is used as a main component of potting mixes for greenhouse-grown plants. (9) Because compost is made from organic waste materials that recently used up CO_2 in the process of their production (plant photosynthesis), compost is considered carbon-neutral, making it a much more environmentally sustainable choice than peat (see Box 12.5).

Disadvantages of Compost. Compost often has low nutrient contents and very slow availability of the nutrients present. It also usually has a relatively high P to N ratio in comparison to plant needs. Because of this ratio, attempts to use compost as the principal source of plant nutrients can easily result in the application of potentially polluting levels of phosphorus (see Section 14.2). In addition, because the more labile organic substances are broken down during the composting process, compost usually provides less benefit to soil aggregation than would the fresh residues from which the compost was made.

12.11 CONCLUSION

Organic matter is a complex and dynamic soil component that exerts a major influence on soil behavior, properties, and functions in the ecosystem. Because of the enormous amount of carbon stored in soil organic matter and the dynamic nature of this soil component, soil management may be an important tool for moderating human-driven climate change.

Organic residue decay, nutrient release, and humus formation are controlled by environmental factors, soil conditions, microbial activities, and by the quality of the organic materials. High contents of lignin and polyphenols, along with high C/N ratios, markedly slow the initial decomposition process, causing organic residues to remain longer while reducing the availability of nutrients.

Soil organic matter can be thought of as comprising two major pools of organic compounds. The *active pool* consists of microbial biomass, soluble carbon compounds, unprotected bits of plant and microbial cells (free POM), and relatively easily decomposed compounds, such as polysaccharides and other high-energy content biomolecules. Although only a small percentage of the total carbon, the active pool plays a major role in nutrient cycling, micronutrient chelation, maintenance of structural stability and soil tilth, and as a food source underpinning biological diversity and activity in soils.

Most of the organic matter is in the *passive pool*, which mainly contains materials that are protected in such a way as to be inaccessible to microbial attack and may persist in the soil for centuries. In many soils, bits of fire-blackened char are also important components of the passive pool. Most char is quite stable and resistant to decomposition, as well as highly porous. Taken together, the passive pool provides cation exchange and water-holding capacities, but is relatively inert biologically. Its relative inertness can change if soil conditions change. When soil is cleared of natural vegetation and brought under cultivation, the initial decline in soil

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organic matter is principally at the expense of the active pool. The passive pool is depleted more slowly and over very long periods of time.

The carbon-to-nitrogen (C/N) ratio of most soils is relatively constant, generally near 12:1. This means that the level of organic matter will be partially determined by the level of nitrogen available for assimilation into humus. Soil management for enhancing long-term organic matter levels must, therefore, include some means of supplying nitrogen, for example, by the inclusion of leguminous plants.

The level of soil organic matter is influenced by climate (being higher in cool, moist regions), drainage (being higher in poorly drained soils), and by vegetation type (being generally higher where root biomass is greatest, as under perennial grasses).

The maintenance of soil organic matter, especially the active pools, in mineral soils is one of the great challenges in natural resource management around the world. By encouraging vigorous growth of crops or other vegetation, abundant residues (which contain both carbon and nitrogen) can be returned to the soil directly or through feed-consuming animals. Also, the rate of destruction of soil organic matter can be minimized by restricting soil tillage, controlling erosion, and keeping most of the plant residues at or near the soil surface.

For some purposes it is advantageous to manage the decomposition of organic matter outside of the soil in a process known as *composting.* Composting transforms various organic waste materials into a dark colored, pleasant smelling product that can be used as a soil amendment or a component of potting mixes. The aerobic decomposition in a compost pile can conserve nutrients while avoiding certain problems, such as noxious odors and the presence of either excessive or deficient quantities of soluble nitrogen, which can occur if fresh organic wastes are applied directly to soils.

The decay and mineralization of soil organic matter is one of the main processes governing the economy of nitrogen and sulfur in soils—the subjects of the next chapter.

STUDY QUESTIONS

1. Compare the amounts of carbon in Earth's standing vegetation, soils, and atmosphere.
2. If you wanted to apply an organic material that would make a long-lasting mulch on the soil surface, you would choose an organic material with what chemical and physical characteristics?
3. Describe how the addition of certain types of organic materials to soil can cause a nitrate depression period. What are the ramifications of this phenomenon for plant growth?
4. What types or categories of organic materials are found in soils?
5. Some scientists include plant litter (surface residues) in their definition of soil organic matter, while others do not. Write two brief paragraphs, one justifying the inclusion of litter as soil organic matter and one justifying its exclusion.
6. What soil properties are mainly influenced by the active and passive pools, respectively, of organic matter?
7. In this book and elsewhere, the terms *soil organic carbon* and *soil organic matter* are used to mean almost the same thing. How are these terms related, conceptually and quantitatively? Why is the term *organic carbon* generally more appropriate for quantitative scientific discussions?
8. Explain, in terms of the balance between gains and losses, why cultivated soils generally contain much lower levels of organic carbon than similar soils under natural vegetation.
9. What is char, how is it produced, and what roles does it play as a component of soil organic matter?
10. In what ways are soils involved in the greenhouse effect that is warming up the Earth? What are some common soil-management practices that could be changed to reduce the negative effects and increase the beneficial effects of soils on the greenhouse effect?
11. Explain why compost is more environmentally sustainable than peat for use in potting media and as an amendment for golf course greens.

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REFERENCES

Bardgett, R. D., and K. F. Chan. 1999. "Experimental evidence that soil fauna enhance nutrient mineralization and plant nutrient uptake in Montane grassland ecosystems." *Soil Biology and Biochemistry* **31**:1007–1014.

Batjes, N. H. 1996. "Total carbon and nitrogen in the soils of the world." *European Journal of Soil Science* **47**:151–163.

Bigelow, C. A., D. C. Bowman, and D. K. Cassel. 2004. "Physical properties of sand amended with inorganic materials or sphagnum peat moss." *USGA Turfgrass and Environmental Research Online* 3(6):1–14. http://usgatero.msu.edu/v03/n06.pdf.

Blanco-Canqui, H., R. Lal, W. M. Post, R. C. Izaurralde, and L. B. Owens. 2006. "Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots." *Soil Science* **171**:468–482.

Blanco-Canqui, H., C. A. Shapiro, C. S. Wortmann, R. A. Drijber, M. Mamo, T. M. Shaver, and R. B. Ferguson. 2013. "Soil organic carbon: The value to soil properties." *Journal of Soil and Water Conservation* **68**:129A–134A.

Cadisch, G., and K. E. Giller (eds.). 1997. *Driven by Nature—Plant Litter Quality and Decomposition*. CAB International, Wallingford, UK.

Campbell, E.E., and K. Paustian. 2015. "Current developments in soil organic matter modeling and the expansion of model applications: A review." *Environmental Research Letters* 10:123004.

Canellas, L., D. Balmori, L. Médici, N. Aguiar, E. Campostrini, R. Rosa, A. Façanha, and F. Olivares. 2013. "A combination of humic substances and herbaspirillum seropedicae inoculation enhances the growth of maize (zea mays l.)." *Plant and Soil*. 366:119–132.

Carlile, W.R., C. Cattivello, and P. Zaccheo. 2015. "Organic growing media: Constituents and properties". *Vadose Zone Journal* 14.

Chen, Y., and T. Aviad. 1990. "Effects of humic substances in plant growth." In P. MacCarthy, C. E. Clapp, R. L. Malcolm, and P. R. Bloom (eds.). *Humic Substances in Soil and Crop Sciences: Selected Readings*. ASA Special Publications, Madison, WI, pp. 161–186.

Cipollini, D., C. Rigsby, and E. K. Barto. 2012. "Microbes as targets and mediators of allelopathy in plants." *Journal of Chemical Ecology* **38**:714–727.

Coppens, F., P. Garnier, A. Findeling, R. Merckx, and S. Recous. 2007. "Decomposition of mulched versus incorporated crop residues: Modelling with pastis clarifies interactions between residue quality and location." *Soil Biology and Biochemistry* **39**:2339–2350.

Curtin, D., M. H. Beare, and G. Hernandez-Ramirez. 2012. "Temperature and moisture effects on microbial biomass and soil organic matter mineralization." *Soil Science Society of America Journal* **76**:2055–2067.

Donato, D. C., J. B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen. 2011. "Mangroves among the most carbon-rich forests in the tropics." *Nature Geoscience* 4:293–297.

Eswaran, H., P. F. Reich, J. Kimble, F. H. Beinroth, E. Padmanabhan, and P. Moncharoen. 2000. "Global carbon stocks." In R. Lal et al. (eds.). *Global Climate Change and Pedogenic Carbonates*. Lewis Publishers, Boca Raton, FL, pp. 15–26.

Ferris, H., R. C. Venette, H. R. van der Meulen, and S. S. Lau. 1998. "Nitrogen mineralization by bacterial-feeding nematodes: Verification and measurement." *Plant and Soil* **203**:159–171.

Haddix, M. L., A. F. Plante, R. T. Conant, J. Six, J. M. Steinweg, K. Magrini-Bair, R. A. Drijber, S. J. Morris, and E. A. Paul. 2011. "The role of soil characteristics on temperature sensitivity of soil organic matter." *Soil Science Society of America Journal* **75**:56–68.

Harden, J. W., C. D. Koven, C.-L. Ping, G. Hugelius, A. D. McGuire, P. Camill, T. Jorgenson, P. Kuhry, G. J. Michaelson, J. A. O'Donnell, E. A. G. Schuur, C. Tarnocai, K. Johnson, and G. Grosse. 2012. "Field information links permafrost carbon to physical vulnerabilities of thawing." *Geophysical Research Letters* **39**:L15704.

Hart, S., and N. Luckai. 2013. "Charcoal function and management in boreal ecosystems." *Journal of Applied Ecology* **50**:1197–1206.

Inderjit, D., A. Wardle, R. Karban, and R. M. Callaway. 2011. "The ecosystem and evolutionary contexts of allelopathy." *Trends in Ecology & Evolution* **26**:655–662.

IPCC. 2007. "Climate change 2007: The physical science basis. Summary for policymakers." [Online]. Intergovernmental Panel on Climate Change, United Nations. Available at http://www.ipcc.ch/SPM2feb07.pdf.

Jenkinson, D. S., and A. E. Johnson. 1977. "Soil organic matter in the Hoosfield barley experiment." *Report of Rothamstead Experimental Station1976* **2**:87–102.

Johnston, A. E., P. R. Poulton, K. Coleman, and L. S. Donald. 2009. "Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes." *Advances in Agronomy*, Vol. 101. Academic Press, London. pp. 1–57.

Kleber, M., and M. G. Johnson. 2010. "Advances in understanding the molecular structure of soil organic matter: Implications for interactions in the environment." *Advances in Agronomy* **106**:77–142.

Laird, D. A., and C.-W. Chang. 2013. "Long-term impacts of residue harvesting on soil quality." *Soil and Tillage Research* **134**:33–40.

Lal, R. 2015. "Sequestering carbon and increasing productivity by conservation agriculture." *Journal of Soil and Water Conservation* **70**:55A–62A.

FOR REFERENCE PURPOSES ONLY

Lal, R. 2016. "Beyond COP 21: Potential and challenges of the "4 per thousand" initiative." *Journal of Soil and Water Conservation* 71:20A–25A.

Lehmann, J., and M. Kleber. 2015. "The contentious nature of soil organic matter." *Nature* 528:60–68.

Lemenih, M., E. Karltun, and M. Olsson. 2005. "Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia." *Agriculture, Ecosystems and Environment* **109**:9–19.

Lynch, D. H., R. P. Voroney, and P. R. Warman. 2006. "Use of 13C and 15N natural abundance techniques to characterize carbon and nitrogen dynamics in composting and in compost-amended soils." *Soil Biology Biochemistry* **38**:1037–1114.

Mackey, B., I. C. Prentice, W. Steffen, J. I. House, D. Lindenmayer, H. Keith, and S. Berry. 2013. "Untangling the confusion around land carbon science and climate change mitigation policy." *Nature Climate Change* **3**:552–557.

Magdoff, F., and R. R. Weil (eds.). 2004. *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL, p. 398.

Mao, J. D., R. L. Johnson, J. Lehmann, D. C. Olk, E. G. Neves, M. L. Thompson, and K. Schmidt-Rohr. 2012. "Abundant and stable char residues in soils: Implications for soil fertility and carbon sequestration." *Environmental Science & Technology* **46**:9571–9576.

Mohr, E. C. J., and P. A. van Baren. 1954. *Tropical Soils*. N. V. Uitgeverij, W. Van Hoeve, The Hague.

Mungai, N. W., and P. P. Motavalli. 2006. "Litter quality effects on soil carbon and nitrogen dynamics in temperate alley cropping systems." *Applied Soil Ecology* **31**:32–42.

Nafziger, E. D., and R. E. Dunker. 2011. "Soil organic carbon trends over 100 years in the morrow plots." *Agronomy Journal* **103**:261–267.

Norse, D. 2012. "Low carbon agriculture: Objectives and policy pathways." *Environmental Development* 1:25–39.

Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes. 2011. "A large and persistent carbon sink in the world's forests." *Science* **333**:988–993.

Paustian, K., and B. Babcock. 2004. "Climate change and greenhouse gas mitigation: Challenges and opportunities." Task Force Report 141. Council on Agricultural Science and Technology, Ames, IA, p. 120.

Poffenbarger, H., S. B. Mirsky, R. R. Weil, J. J. Meisinger, J. E. Maul, M. A. Cavigelli, and J. T. Spargo. 2015. "Legumegrass proportions, poultry litter, and tillage effects on cover crop decomposition." *Agronomy Journal* 107:2083–2096.

Redeker, K., N. Wang, J. Low, A. McMillan, S. Tyler, and R. Cicerone. 2000. "Emissions of methyl halides and methane from rice paddies." *Science* **290**:966–969.

Scharlemann, J. P. W., R. Hiederer, V. Kapos, and C. Ravilious. 2010. "Updated global carbon map." United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK. http://esdac.jrc.ec.europa.eu/ESDB_Archive/octop/Resources/Global_OC_Poster.pdf.

Schmidt, M. W. I., and A. G. Noack. 2000. "Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges." *Global Biogeochemical Cycles* **14**:777–793.

Schmidt, M. W. I., M. S. Torn, S. Abiven, T. Dittmar, G. Guggenberger, I. A. Janssens, M. Kleber, I. Kogel-Knabner, J. Lehmann, D. A. C. Manning, P. Nannipieri, D. P. Rasse, S. Weiner, and S. E. Trumbore. 2011. "Persistence of soil organic matter as an ecosystem property." *Nature* **478**:49–56.

Seghers, D., S. D. Siciliano, E. M. Top, and W. Verstraete. 2005. "Combined effect of fertilizer and herbicide applications on the abundance, community structure and performance of the soil methanotrophic community." *Soil Biology and Biochemistry* **37**:187–193.

Senesi, N., B. Xing, and P. M. Huang. 2009. *Biophysico-Chemical Processes Involving Natural Nonliving Organic Matter in Environmental Systems* John Wiley & Sons, Hoboken, NJ. 876 p.

Singh, N., S. Abiven, M. S. Torn, and M. W. I. Schmidt. 2012. "Fire-derived organic carbon in soil turns over on a centennial scale." *Biogeosciences* **9**:2847–2857.

Tian, G. B., L. Brussaard, and B. T. Kang. 1995. "An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics." *Applied Soil Ecology* **2**:25–32.

Tian, G., B. T. Kang, and L. Brussaard. 1992. "Biological effects of plant residues with contrasting chemical compositions under humid, tropical conditions—Decomposition and nutrient release." *Soil Biology and Biochemistry* **24**:1051–1060.

Torbert, H., and H. Johnson. 2001. "Soil of the intensive agriculture biome of Biosphere 2." *Journal of Soil Water Conservation* **56**:4–11.

USEPA. 2011. Draft inventory of U.S. Greenhouse gas emissions and sinks: 1990-2009, Washington, DC. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

Walford, R. L. 2002. "Biosphere 2 as voyage of discovery: The serendipity from inside." *BioScience* **52**:259–263.

Weil, R. R., K. R. Islam, and C. L. Mulchi. 2000. "Impact of elevated CO_2 and ozone on C cycling processes in soil." *Agronomy Abstracts*. American Society of Agronomy, Madison, WI, p. 47.

Zackrisson, O., M.-C. Nilsson, and D. A. Wardle. 1996. "Key ecological function of charcoal from wildfire in the boreal forest." *Oikos* **77**:10–19.

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Legume, red clover, enriches soil with nitrogen. (Ray R. Weil)

13 Nitrogen and Sulfur Economy of Soils

The pulse and body of the soil …
—D. H. Lawrence, The Rainbow

The biogeochemistries of nitrogen and sulfur have much in common. Both are essential nutrients found primarily in organic forms in soils. Both move in soils and plants mostly in the form of anions. Both undergo oxidation and reduction to form gases, and both are responsible for serious environmental problems. This chapter explores the stories of these two elements, starting with nitrogen.[1]

More money and effort are spent on the management of nitrogen than on any other nutrient element, and for good reason. Deficiencies or excesses of nitrogen have major impacts on the health and productivity of the world's ecosystems. Were it not for the biological fixation of nitrogen from the atmosphere by certain soil microbes, and for the recycling back to the soil of much of the nitrogen taken up by the vegetation, deficiencies of nitrogen would be ubiquitous, and most ecosystems would grind to a halt. Where humans harvest food from the land, these cycles have been disrupted. Yellowish leaves of nitrogen-starved crops forebode hunger or financial ruin for people in all corners of the globe. Nitrogen fertilizer is an expensive but often necessary input in agricultural systems. Its manufacture accounts for a large part of the fossil fuel energy used by the agricultural sector. The quest for protein—which contains about one-sixth nitrogen—by billions of humans is fueling demand for nitrogen fertilizer and transforming both global agriculture and the global N cycle.

Nitrogen excesses are now nearly as common as deficiencies and can adversely affect both human and ecosystem health. Nitrogen leaking from overly enriched soils can lead to nitrate pollution of groundwater, making it unfit for human or animal consumption. In addition, the movement of soluble nitrogen compounds from soils to aquatic systems can disrupt the balance of those systems, leading to algae blooms, declining levels of dissolved oxygen, and subsequent death of fish and other aquatic species. Yet another way in which nitrogen links soils to the wider environment is the ozone-destroying and climate-forcing action of nitrous oxide gas generated in soils. Clearly, soil processes are central to the global nitrogen cycle. The ecological, financial, and environmental stakes for the management of soil nitrogen are very high, indeed.

[1]For a review of nitrogen in agriculture, with special emphasis on environmental and human health impacts, see Addiscott (2005). For how nitrogen interacts with Earth's ecosystems, see Gruber and Galloway (2008). For current and future global nitrogen cycle processes under climate change, see Fowler et al. (2015).

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13.1 INFLUENCE OF NITROGEN ON PLANT GROWTH AND DEVELOPMENT

Roles in the Plant. Healthy plant foliage generally contains 2.0–4.0% nitrogen, depending on plant species and age of the leaves. Nitrogen is an integral component of many essential plant compounds. It is a major part of all amino acids, the building blocks of all proteins—including the enzymes, which control virtually all biological processes. Other critical nitrogenous plant components include the nucleic acids, in which hereditary control is vested, and chlorophyll, which is at the heart of photosynthesis. Nitrogen is also essential for carbohydrate use within plants. A good supply of nitrogen stimulates root growth and development, as well as the uptake of other nutrients.

Plants respond quickly to increased availability of nitrogen, their leaves turning deep green in color. Nitrogen increases the plumpness of cereal grains, the protein content of both seeds and foliage, and the succulence of leaves, stems and tubers. It can dramatically stimulate plant productivity, whether measured in tons of grain, volume of lumber, carrying capacity of pasture, or thickness of lawn.

Deficiency. Plants deficient in nitrogen tend to exhibit chlorosis (yellowish or pale green leaf colors), a stunted appearance, and thin, spindly stems (Figure 13.1). In nitrogen-deficient plants, the protein content is low and the sugar content is usually high, because carbon compounds normally destined to build proteins cannot do so without sufficient nitrogen. Nitrogen is quite mobile (easily translocated) within the plant. When plant uptake is inadequate, nitrogenous compounds in the oldest leaves are broken down and the nitrogen transferred to the newest foliage, causing the older leaves to show pronounced chlorosis. The older leaves of nitrogen-starved plants are therefore the first to turn yellowish, typically becoming prematurely senescent and dropping off (Figures 13.1*a*,*b*). Nitrogen-deficient plants often have a low shoot-to-root ratio, and they mature more quickly than healthy plants. The negative effects of nitrogen deficiency on plant size and vigor are often dramatic (Figure 13.1*a*).

Oversupply. When too much nitrogen is available, excessive vegetative growth occurs; the cells of the plant stems become enlarged but relatively weak, and the top-heavy plants are prone to falling over (lodging) with heavy rain or wind (Figure 13.1*d*). High nitrogen applications may delay plant maturity and cause the plants to be more susceptible to disease (particularly fungal disease) and to insect pests. These problems are especially noticeable if other nutrients, such as potassium, are in relatively low supply.

An oversupply of nitrogen degrades crop quality, resulting in undesirable color and flavor of fruits and low sugar and vitamin levels of certain vegetables and root crops. Flower production in ornamentals is reduced in favor of abundant foliage. An oversupply can also cause the buildup of nitrogen in the form of nitrates that are harmful to livestock in the case of forage and to babies in the case of leafy vegetables. Growth-inhibiting environmental conditions (e.g., drought; dark, cloudy days; or cool temperatures) can exacerbate the accumulation of nitrate in tissues because plant conversion of nitrate into protein is slowed. The leaching of excess nitrogen from the soil is a major water pollution problem particularly degrading to groundwater and downstream estuaries (see Sections 13.14 and 16.2).

Forms of Nitrogen Taken up by Plants. Plant roots take up nitrogen from the soil principally as dissolved nitrate (NO_3^-) and ammonium (NH_4^+) ions. Although certain plants grow best when provided mainly with one or the other of these forms, a relatively equal mixture of the two ions gives the best results with most plants. As explained in Chapter 9 (see Sections 9.1 and 9.5 and Figure 9.14), uptake of ammonium markedly lowers the pH of the rhizosphere soil while uptake of nitrate tends to have the opposite effect. These pH changes, in turn, influence the uptake of other ions such as phosphates and micronutrients. In addition to NO_3^- and NH_4^+ ions, nitrite ions (NO_2^-) can also be taken up, but fortunately only trace quantities of this toxic ion usually occur in field soils.

Although NO_3^- and NH_4^+ ions are the dominant forms of N taken up by plants in many systems, numerous plants have been shown to also take up low molecular weight dissolved organic compounds (mainly soluble proteins, amino acids, and urea). Generally, when soluble

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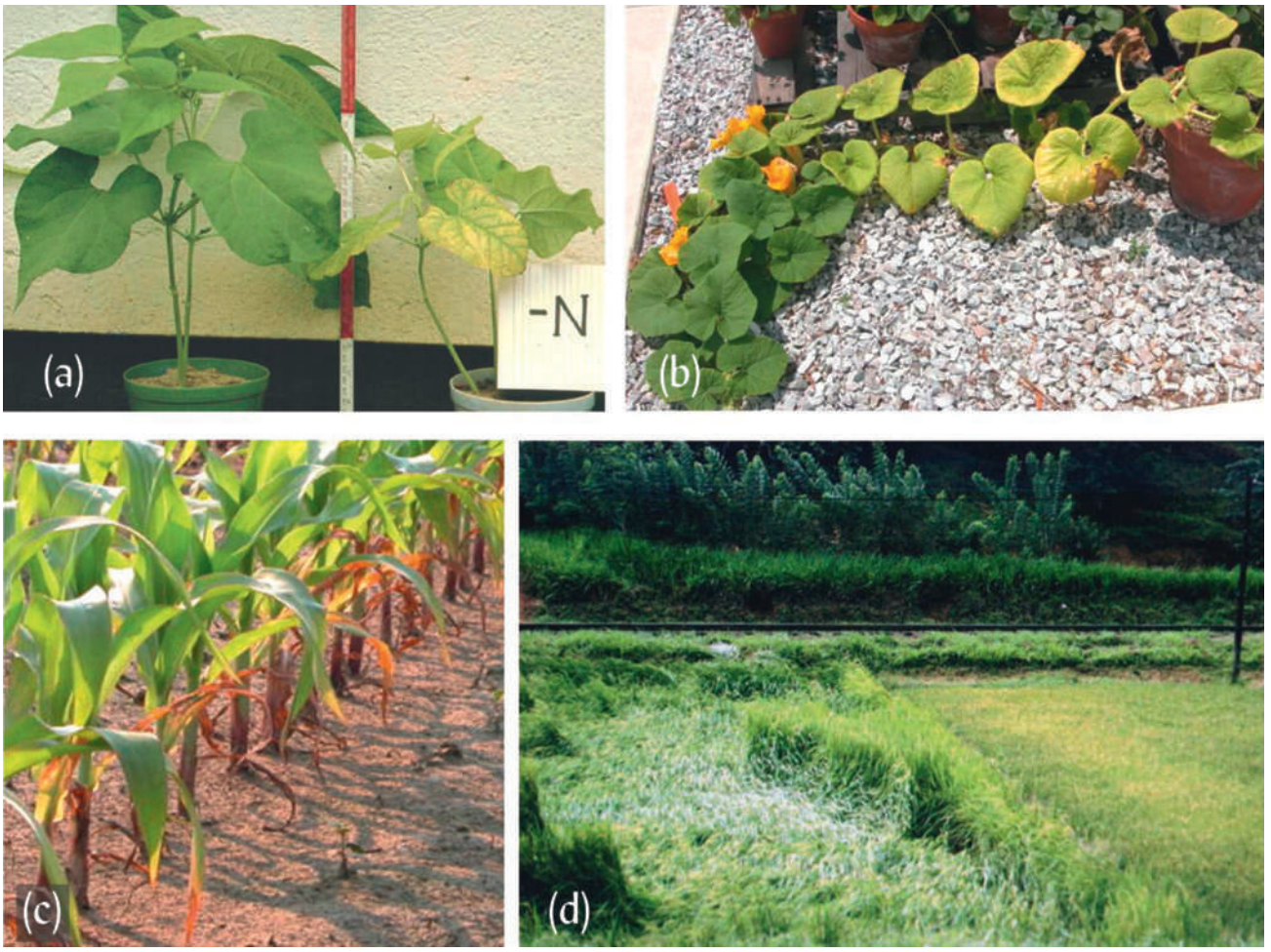

Figure 13.1 *Symptoms of too little and too much nitrogen. (a) The nitrogen-starved bean plant (right) shows the typical chlorosis of lower leaves and markedly stunted growth compared to the normal plant on the left. (b) The oldest leaves at right near the base of this potted cucurbit vine are chlorotic because N has been transferred to the newest leaves on the left which are dark green. (c) The oldest bottom corn leaves yellowed, beginning at the tip and continuing down the midrib—a pattern typical of nitrogen deficiency in corn. (d) Asian rice heavily fertilized with nitrogen. The traditional tall cultivar in the left field has lodged (fallen over), but the modern rice cultivar at right yields well with high nitrogen inputs because of its short stature and stiff straw.* (Photos courtesy of Ray R. Weil)

organic and inorganic N sources are both present in equal amounts, the plant uptake of organic N is an order of magnitude smaller than the uptake of mineral N. However, there is much variation, even within a family of plants. For example, among the Gramineae, sorghum and rice seem to efficiently take up soluble protein N, while corn and millet do not. Also, some evidence suggests that if grown with soil solutions relatively high in organic N and low in inorganic N, some plant species may become conditioned to utilize organic N more effectively. The direct uptake of soluble organic N is of particular significance in natural grasslands and forests.

13.2 DISTRIBUTION OF NITROGEN AND THE NITROGEN CYCLE[2]

Most of Earth's nitrogen is either in the atmosphere (about 4,000 Eg = exagrams = 10^{18} g) or in crustal rocks (about 2,000 Eg). We will not consider here the vast pool of N contained in igneous rocks deep in the planet's crust, where it is effectively out of contact with the

[2]To read about the evolution of Earth's nitrogen cycle, its disruption during the past century by industrial agriculture, and its inevitable microbial rebalancing, with or without human adaptation, see Canfield et al. (2010).

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biosphere.[3] The air above each hectare of the Earth's surface contains some 75,000 Mg of nitrogen. The atmosphere, which is 78% gaseous nitrogen (N_2), would appear to be a virtually limitless reservoir of this element. However, the very stable triple bond between two nitrogen atoms (N≡N) makes this gas extremely inert and not directly usable by plants or animals. Little nitrogen would be found in soils and little vegetation would grow in terrestrial ecosystems around the world were it not for certain natural processes (principally nitrogen fixation by microbes and lightning) that can break this triple bond and form **reactive nitrogen** (see Section 13.10). In reactive nitrogen compounds the N is usually bonded to hydrogen, oxygen, or carbon (e.g., NH_4^+, NO_3^-, N_2O, and amino acids, R—C—NH_2) making it easily used in a variety of biological and chemical reactions.

Much of the reactive N is mobile and large amounts move between the atmosphere, the land, and the oceans (Figure 13.2). Nitrogen moves from the atmospheric N≡N pool to the terrestrial and marine reactive N pools mainly by various categories of nitrogen fixation (Section 13.9). Burning of fossil fuels also adds reactive N, initially mainly to the land. Nitrogen is transferred from land to water and eventually to the oceans principally by leaching of nitrates and dissolved organic nitrogen (DON) and by atmospheric deposition. Finally, the cycle is brought full circle with the transfer of reactive nitrogen from land and water back to the atmosphere as N≡N and other nitrogen-containing gases, principally by certain microbial processes termed **denitrification** (see Section 13.8 and 13.9).

Most of the nitrogen in terrestrial systems is found in the soil, with A horizons normally ranging from 0.02 to 0.5% N by weight. A value of about 0.15% N would be representative for cultivated soils. A hectare of such a soil would contain about 3.5 Mg nitrogen in the A horizon and perhaps an additional 3.5 Mg in the deeper layers. In forests, the litter layer (O horizons) might contain 1–2 Mg of nitrogen in addition to that in the mineral soil. Thus, soils contain 10–20 times as much nitrogen as does the standing vegetation (including roots) of either forested or cultivated areas.

Most soil nitrogen is present as part of organic molecules, therefore, the distribution of soil nitrogen closely parallels that of soil organic matter (SOM), which typically contains about 5% nitrogen (see Sections 12.3 and 12.10).

Except where large amounts of chemical fertilizers have been applied, inorganic (i.e., mineral) nitrogen seldom accounts for more than 1–2% of the total nitrogen in the soil. Unlike the bulk of organic nitrogen, most mineral forms of nitrogen are quite soluble in water and may be easily lost from soils through leaching and volatilization.

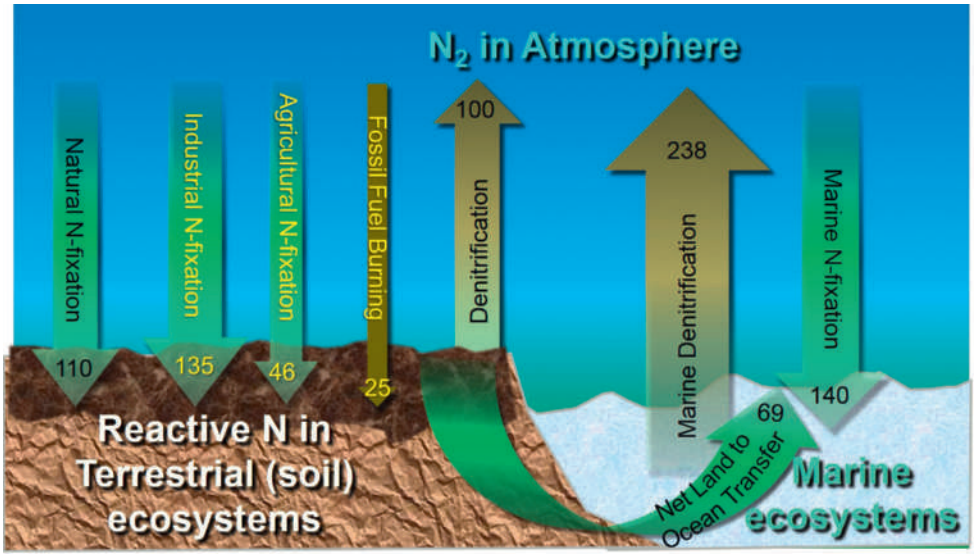

Figure 13.2 *The movement of nitrogen between Earth's atmosphere (mainly N≡N), land masses (terrestrial ecosystems), and oceans (marine ecosystems). The arrows are labeled with the general processes they represent and the numbers in each arrow indicate the estimated global annual nitrogen flux in Tg/yr (teragrams or 10^{12} g per year) via each process. The three main anthropogenic processes are labeled in yellow.* (Redrawn and recalculated from data in Canfield et al. (2010))

[3]The weathering of certain N-rich sedimentary rocks at the Earth's surface may, however, contribute significant amounts of N to both forest tree nutrition and N loading to rivers in drainage water (Morford et al., 2011).

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The Nitrogen Cycle

The nitrogen cycle has long been the subject of intense scientific investigation, because understanding the translocations and transformations of this element is fundamental to solving many environmental, agricultural, and natural resource–related problems. As an atom of nitrogen moves through the nitrogen cycle it appears in many different chemical forms. Each form has its own properties, behaviors, and consequences for the ecosystem. This cycle explains why vegetation (and, indirectly, animals) can continue to remove nitrogen from a soil for centuries without depleting the soil of this essential nutrient. The **biosphere** does not run out of nitrogen (or other nutrient elements) because it uses the same atoms over and over again. This cycling of N is highly visible in Figure 11.31, which shows a dark green circle of grass plants that have responded to the fungal release of N from the residues of previous grass growth.

The principal pools and forms of nitrogen, and the processes by which they interact in the cycle, are illustrated in Figure 13.3. This figure deserves careful study; we will refer to it frequently as we discuss each of the major processes of the nitrogen cycle.

Ammonium (NH_4^+) and nitrate (NO_3^-) are two critical forms of inorganic nitrogen which are subject to various fates in the N cycle (see the arrows *leaving* the nitrate and ammonium boxes in Figure 13.3). In addition to its possible loss by erosion and runoff, the N in NH_4^+ can be subject to at least six fates: (1) *immobilization* by microorganisms; (2) removal by *plant uptake*; (3) *anammox*—the anaerobic oxidation of NH_4^+ in conjunction with nitrite (NO_2^-) to produce N_2O gas; (4) *volatilization* after being transformed into ammonia gas; (5) *nitrification*—the microbial oxidation of ammonium to nitrite and subsequently to nitrate; and (6) *fixation* or strong sorption in the interlayers of certain 2:1 clay minerals.

Similarly, in addition to loss by erosion and runoff, the N in NO_3^- is subject to six possible fates (note that some of these fates are shared with the N in NH_4^+): (1) *immobilization* by microorganisms; (2) removal by *plant uptake*; (3) microbial reduction to NO_2^- followed by conversion, along with ammonium, by *anammox* to N_2O gas; (4) *denitrification*—microbial reduction forming N_2 and other nitrogen-containing gases which are lost to the atmosphere; (5) *dissimilatory reduction* by microbes to ammonium; and (6) loss to groundwater by *leaching* in drainage water. We will discuss these N transformations in subsequent sections of this chapter.

13.3 IMMOBILIZATION AND MINERALIZATION

Most (95–99%) soil nitrogen exists in large organic molecules that protect it from loss but also leave it unavailable for uptake by plant roots. Microbial decomposition breaks these large, insoluble N-containing organic molecules into smaller and smaller units with the eventual production of simple amino compounds,[4] or amine groups ($R—NH_2$). Then the amine groups are hydrolyzed, and the nitrogen is released as ammonium ions (NH_4^+), which can be oxidized to the nitrate form. The enzymes that bring about this process are produced mainly by microorganisms (but some are produced by plant roots and soil animals) and include hydrolases and deaminases that break C—H and $C—NH_2$ bonds. The enzymes may carry out the reactions inside microbial cells, but most often they are excreted by the microbes and work extracellularly in the soil solution or while adsorbed to colloidal surfaces. This enzymatic process termed **mineralization** (Figure 13.3) may be indicated as follows, using an amino compound ($R—NH_2$) as an example of the organic nitrogen source:

$$\xrightarrow{\qquad\qquad\text{Mineralization}\qquad\qquad}$$

$$R—NH_2 \underset{-2H_2O}{\overset{+2H_2O}{\rightleftharpoons}} OH^- + R—OH + NH_4^+ \underset{-O_2}{\overset{+O_2}{\rightleftharpoons}} 4H^+ + \text{energy} + NO_2^- \underset{-1/2O_2}{\overset{+1/2O_2}{\rightleftharpoons}} \text{energy} + NO_3^-$$

$$\xleftarrow{\qquad\qquad\text{Immobilization}\qquad\qquad} \tag{13.1}$$

[4]Amino acids such as lysine (CH_2NH_2COOH) and alanine (CH_3CHNH_2COOH) are examples of these simpler compounds. The R in the generalized formula represents the part of the organic molecule with which the amino group (NH_2) is associated. For example, for lysine, the R is CH_2COOH.

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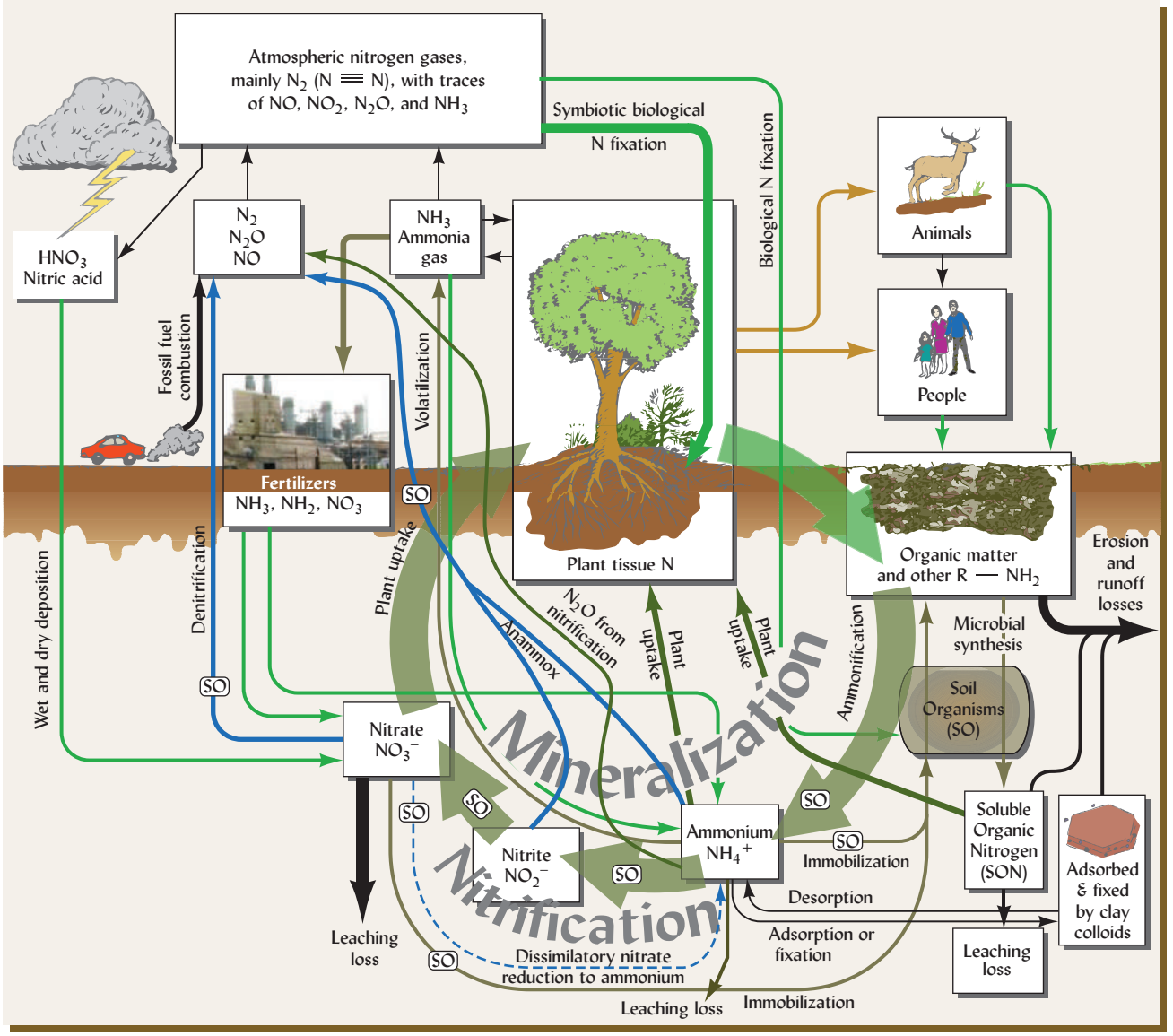

Figure 13.3 *The nitrogen cycle encompasses many translocations and transformations. Here it is shown emphasizing the primary cycle in aerobic soils (thick olive green arrows) in which microbes mineralize organic nitrogen from plant residue, plants take up the mineral nitrogen, and eventually return organic nitrogen to the soil as fresh plant residues. In this regard N is like any of the other plant nutrients that cycle through soils. However, because nitrogen exists in many valence states and in all three phases of matter (gas, liquid, and solid), its interactions and cycling pathways are much more complex than just this basic cycle. The boxes represent various forms of nitrogen. The arrows represent processes by which one form is transformed into another. The name of a process (e.g., Mineralization or Anammox) is given alongside the arrow. Note the processes by which nitrogen is lost from the soil and by which it is replenished (bright green arrows). The blue arrows represent anaerobic processes. Soil organisms, whose enzymes drive most of the reactions in the cycle, are represented as rounded boxes labeled "SO."* (Diagram courtesy of Ray R. Weil)

Many studies have shown that about 1.5–3.5% of the organic nitrogen in A horizon soil mineralizes annually.[5] In most soils, this rate of mineralization provides sufficient mineral nitrogen for normal growth of natural vegetation; in soils with relative high levels of organic matter, mineralization may provide enough mineral N for good crop yields, as well. Furthermore, *isotope tracer studies* of farm soils that have been amended with synthetic nitrogen

[5]Studies using ^{15}N tracers suggest that the rate of mineralization of fertilizer nitrogen that had been immobilized the previous year can be as much as seven times these modest rates.

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fertilizers show that mineralized soil nitrogen constitutes a major part of the nitrogen taken up by crops. If the organic matter content of a soil is known, one can make a rough estimate of the amount of nitrogen likely to be mineralized during a typical growing season (Box 13.1).

The opposite of mineralization is **immobilization**, the conversion of inorganic nitrogen ions (NO_3^- and NH_4^+) into organic forms (see Eq. (13.1) and Figure 13.3). Immobilization can take place by both biological and nonbiological (abiotic) processes. The latter probably involves chemical reactions with high C/N ratio organic matter and can be quite important in forested soils (Figure 13.4).

Most nitrogen immobilization occurs biologically when microorganisms decomposing organic residues require more nitrogen than they can obtain from the residues they are metabolizing. The microorganisms then scavenge NO_3^- and NH_4^+ ions from the soil solution to incorporate into such cellular components as proteins, leaving the soil solution essentially devoid of mineral N. When the organisms die, some of the organic nitrogen in their cells may be converted into forms that make up the SOM, and some may be released as NO_3^- and NH_4^+ ions. Mineralization and immobilization occur simultaneously in the soil; whether the *net* effect is an increase or a decrease in the mineral nitrogen supply depends primarily on the ratio of carbon to nitrogen in the organic residues undergoing decomposition (see Section 12.3).

BOX 13.1

CALCULATION OF NITROGEN MINERALIZATION

If the organic matter content of a soil, management practices, climate, and soil texture are known, it is possible to make a rough estimate of the amount of N likely to be mineralized each year. The following equation may be used:

$$\frac{\text{kg N mineralized}}{\text{ha 15 cm deep}} = \left(\frac{A\text{ kg SOM}}{100\text{ kg soil}}\right)\left(\frac{B\text{ kg soil}}{\text{ha 15 cm deep}}\right)\left(\frac{C\text{ kg N}}{100\text{ kg SOM}}\right)\left(\frac{D\text{ kg SOM mineralized}}{100\text{ kg SOM}}\right) \quad (13.2)$$

where A = The amount of SOM in the upper 15 cm of soil, given in kg SOM per 100 kg soil (this is same value as the % SOM as is often reported by test labs). This value may range from close to zero to over 75% (in a Histosol) (see Section 3.9). Values between 0.5 and 5% are most common. ☞ Use a value of 2.5% (2.5 kg SOM/100 kg soil) for the example shown below.

B = For the weight of soil per hectare to the depth of 15 cm, 2×10^6 kg/ha is a reasonable estimate. See Section 4.7 to calculate the weight of such a soil layer if bulk density of a soil is known. In some soils it may be important to also consider deeper layers. ☞ Use 2×10^6 kg soil/ha 15 cm deep in the example shown below.

C = The amount of nitrogen in the SOM (see Section 12.3). ☞ Use the typical figure of 5 kg N/100 kg SOM in the example shown below.

D = The amount of SOM likely to be mineralized in one year for a given soil. This figure depends upon the soil texture, climate, and management practices. Values of around 2% are typical for a fine-textured soil, while values of around 3.5% are typical for coarse-textured soils. Slightly higher values are typical in warm climates; slightly lower values are typical in cool climates. ☞ Assume a value of 2.5 kg SOM mineralized/100 kg SOM for the example shown below.

The amount of nitrogen likely to be released by mineralization during a typical growing season may be calculated by substituting the example values given above:

$$\frac{\text{kg N mineralized}}{\text{ha 15 cm deep}} = \left(\frac{2.5\text{ kg SOM}}{100\text{ kg soil}}\right)\left(\frac{2 \times 10^6\text{ kg soil}}{\text{ha 15 cm deep}}\right)\left(\frac{5\text{ kg N}}{100\text{ kg SOM}}\right)\left(\frac{2.5\text{ kg SOM mineralized}}{100\text{ kg SOM}}\right)$$

$$\frac{\text{kg N mineralized}}{\text{ha}} = \left(\frac{2.5}{100}\right)\left(\frac{2 \times 10^6}{1}\right)\left(\frac{5}{100}\right)\left(\frac{2.5}{100}\right) = 62.5\text{ kg N/ha}$$

Most nitrogen mineralization occurs during the growing season when the soil is relatively moist and warm. Contributions from the deeper layers of this soil might be expected to bring total nitrogen mineralized in the root zone of this soil during a growing season to over 120 kg N/ha.

These calculations estimate the nitrogen mineralized annually from a soil that has not had large amounts of organic residues added to it. Animal manures, legume residues, or other nitrogen-rich organic soil amendments would mineralize much more rapidly than the native SOM and thus would substantially increase the amount of nitrogen available in the soil.

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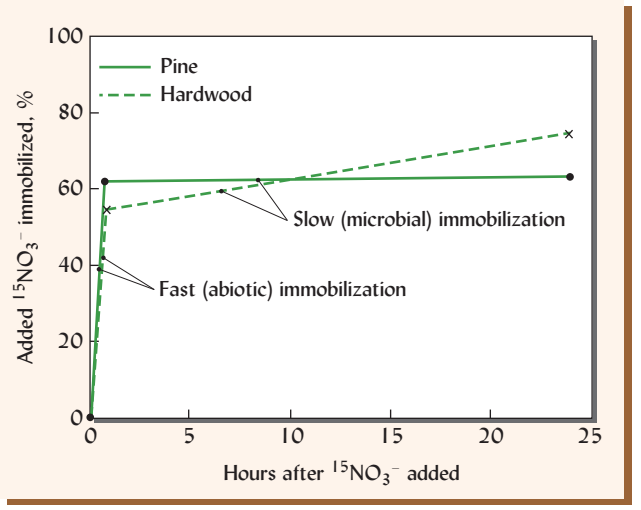

Figure 13.4 *The rate of immobilization of ^{15}N-labeled nitrate added in solution to samples of forest soils where either pine or hardwood stands prevailed. Very rapid immobilization took place in both soils during the first hour, apparently by nonbiological (abiotic) processes. The nitrates probably reacted chemically with the soil organic matter. This fast reaction was followed by the more commonly observed slower immobilization in response to biological reactions stimulated by soil microorganisms. This graph suggests that both biological and abiotic reactions must be taken into consideration in studying the nitrogen-retentive capacity of forest soils.* (Redrawn from data in Bernston and Aber (2000))

13.4 DISSOLVED ORGANIC NITROGEN[6]

Until recently, most studies of nitrogen uptake and leaching focused exclusively on mineral N, especially nitrate. However, modern analytical tools have now shown conclusively that plant uptake and leaching losses in both natural and agroecosystems involved nitrogen-containing organic compounds. These compounds either actually exist dissolved in the soil solution (DON) or can be easily extracted out of soil samples using simple salt solutions (SON). Thus the DON is a portion of the SON (Figure 13.5). The DON generally accounts for between 0.1 and 3% of the total N in soils, a pool size similar to that of mineral nitrogen (NH_4^+ and NO_3^-). In fact, where organic manures have been applied to arable soils or where animal urine is applied to grassland, DON contents are often considerably higher than those of mineral nitrogen. The nitrogen mobilized from the litter of some forest species may have DON:inorganic N ratios of 10:1 or higher.

Plant Uptake of DON. In nitrogen-limited ecosystems, such as those in strongly acidic and infertile soils (including some organic soils), DON may be the primary source of absorbed nitrogen. This helps explain the fact that plant growth, particularly of some forest species, is considerably greater than one would expect based on the limited supply of inorganic nitrogen at any one time. Low molecular weight compounds in the DON, such as amino acids, may be taken up directly by plant roots, or they may be assimilated through mycorrhizal associations.

Figure 13.5 *Soluble organic nitrogen (SON) is comprised of compounds that can be easily dissolved in water or mild salt solutions. It is a small portion of the total organic N. The SON is potentially subject to leaching loss and—in case of the smaller soluble molecules—to absorption by plant roots. The measured size of the SON pool depends on the particular lab method used to extract it from the soil. The portion of the SON that is actually dissolved in the soil solution at a given time is termed the dissolved organic nitrogen (DON). Thus the DON measured in soil solution or leachates in the field is part of a larger pool of SON which can be measured by lab extraction, and which in turn comprises a few percent of the total organic nitrogen in a soil.* (Diagram courtesy of Ray R. Weil)

[6]For reviews of the nature, significance, and analyses of soluble organic nitrogen, see Ros et al. (2009) for agricultural soils and van Kessel et al. (2009) for a focus on natural ecosystems.

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Most root uptake of nitrogen from DON occurs, however, after the readily decomposable organic N compounds are mineralized to NH_4^+ and NO_3^- ions.

Microbial Utilization. Low molecular weight DON compounds can be transported into microbial cells for direct assimilation. Once inside the microbial cell, enzymes decompose these DON compounds, and the N is used to make proteins and other components needed by the microbe. If the N from the DON exceeds the immediate need in the cell, the excess will be released back into the soil solution (mineralization). Microbial uptake of both DON and mineral N take place concurrently in soils, giving rise in some soils to direct competition between plants and microbes for both forms of nitrogen.

Leaching Potential of DON. Dissolved organic nitrogen is also a significant component of the N lost by leaching. For example, DON may comprise nearly all the N leached from some pristine forests and typically 30–60% of that leached from dairy farms and beef feedlots. In fact, DON comprises about 25% of the N carried by the Mississippi River into the Gulf of Mexico. Thus, DON likely contributes to the environmental problems downstream and should be studied along with nitrate N to understand and solve nitrogen-pollution problems.

Chemical Makeup of DON. The chemical constituents of DON are believed to originate from microbial and root exudates and litter leachates, as well as hydrolyzed insoluble organic matter. We know that some of the compounds are hydrophilic and that others are hydrophobic. This suggests some may be able to interact with inorganic colloids, but others would react primarily with SOM. About a third of the DON is in the form of amino compounds such as amino sugars and amino acids. However, more research is needed to further ascertain the compounds that make up DON and the role they play in soil and related ecosystems.

13.5 AMMONIUM FIXATION BY CLAY MINERALS

Like other positively charged ions, ammonium ions are attracted to the negatively charged surfaces of clay and humus, where they are held in exchangeable form, available for plant uptake, but partially protected from leaching (see Section 8.7). However, because of its particular size, the ammonium ion (as well as the similarly sized potassium ion) can become entrapped or *fixed* within cavities in the crystal structure of certain 2:1-type clay minerals. Vermiculite has the greatest capacity for such ammonium (and potassium) fixation, followed by fine-grained micas and some smectites (see Figures 8.16 and 14.43 and 14.44). Ammonium and potassium ions fixed in the rigid part of a crystal structure are held in a nonexchangeable form, from which they are released only slowly. This use of the term *fixation* should not be confused with its use regarding biological nitrogen fixation, a process by which inert atmospheric N_2 gas is fixed in reactive, plant available forms (see Section 13.10).

Ammonium fixation by clay minerals is generally greater in subsoil than in topsoil, due to the higher clay content of subsoils (Table 13.1). In soils with considerable 2:1 clay content, interlayer-fixed NH_4^+ typically accounts for 5–10% of the total nitrogen in the surface soil and up to 20–40% of the nitrogen in the subsoil. In highly weathered soils, on the other hand, ammonium fixation is minor because little 2:1 clay is present. In some forest soils, about half the nitrogen in the O and A horizons is immobilized by either ammonium fixation or chemical reactions with humus. While ammonium fixation may be considered an advantage because it provides a means of conserving nitrogen, the rate of release of the fixed ammonium is often too slow to be of much practical value in fulfilling the needs of fast-growing annual plants.

13.6 AMMONIA VOLATILIZATION

Ammonia gas (NH_3) can be produced from the breakdown of plant residues, animal excrement, and from such fertilizers as anhydrous ammonia and urea. This gas may diffuse into the atmosphere, resulting in a loss of valuable nitrogen from the soil and environmentally

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Table 13.1
TOTAL NITROGEN LEVELS OF A AND B HORIZONS OF FOUR CULTIVATED VIRGINIA SOILS AND THE PERCENTAGE OF THE NITROGEN PRESENT AS NONEXCHANGEABLE OR FIXED NH_4^+.
Note the Higher Percentage of Fixation in the B Horizon

	Total N, mg/kg		Nitrogen fixed as NH_4^+, %	
Soil great group (series)	A horizon	B horizon	A horizon	B horizon
Hapludults (Bojac)	812	516	5	18
Paleudults (Dothan)	503	336	5	14
Hapludults (Groseclose)	1792	458	3	17
Hapludults (Elioak)	1110	383	6	26

Source: From Baethgen and Alley (1987).

detrimental increases on nitrogen deposition from the atmosphere (see Section 13.12). The ammonia gas is in equilibrium with ammonium ions according to the following reversible reaction:

$$\underset{\text{Dissolved ions}}{NH_4^+ + OH^-} \rightleftharpoons H_2O + \underset{\text{Gas}}{NH_3\uparrow} \qquad (13.3)$$

From Reaction (13.3) we can draw two conclusions. First, ammonia volatilization will be more pronounced at high pH levels (i.e., OH^- ions drive the reaction to the right); second, ammonia gas–producing amendments or the addition of water will drive the reaction to the left, raising the pH of the solution in which they are dissolved.

Soil colloids, both clay and humus, adsorb ammonia gas, so ammonia losses are greatest where low quantities of these colloids are present or where the ammonia is not in close contact with the soil. For these reasons, ammonia losses can be quite large from sandy soils and from alkaline or calcareous soils, especially when the ammonia-producing materials are left at or near the soil surface and when the soil is drying out. High temperatures, as often occur on the surface of the soil, also favor the volatilization of ammonia (Figure 13.6).

Incorporation of manure and fertilizers into the top few centimeters of soil can reduce ammonia losses by 25–75% from those that occur when the materials are left on the soil surface. In natural grasslands and pastures, incorporation of animal wastes by earthworms and dung beetles is critical in maintaining a favorable nitrogen balance and a high animal-carrying capacity in these ecosystems (see Section 11.2). A well-timed application of irrigation water can greatly reduce the loss of NH_3 gas from surface-applied fertilizers (Figure 13.7).

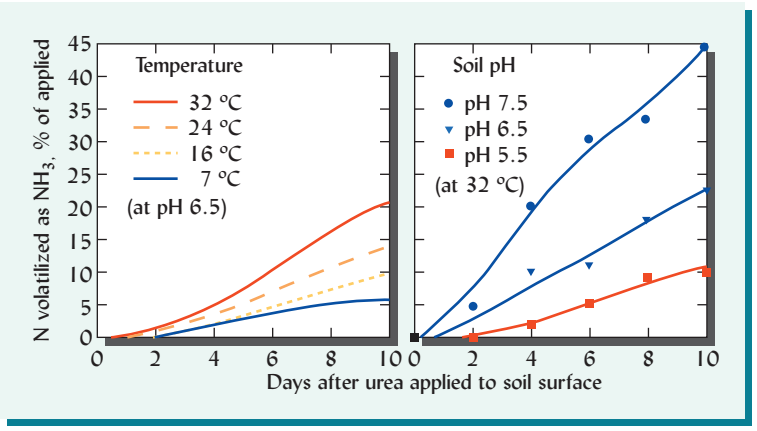

Figure 13.6 *Ammonia volatilization is markedly affected by temperature and pH. Here, urea fertilizer (NH_2—CO—NH_2) was applied to a silt loam soil surface. Urea absorbs moisture from the air or soil and then hydrolyzes to form ammonia. The loss of ammonia gas is especially rapid when pH exceeds 7 and temperature exceeds 16 °C. Ammonia loss can be even faster from animal feces (manure) than from urea. Ammonia-forming amendments should not be left on the surface of warm, high pH soil for more than a day.* [Redrawn from Glibert et al. (2006) using data in Franzen (2004)]

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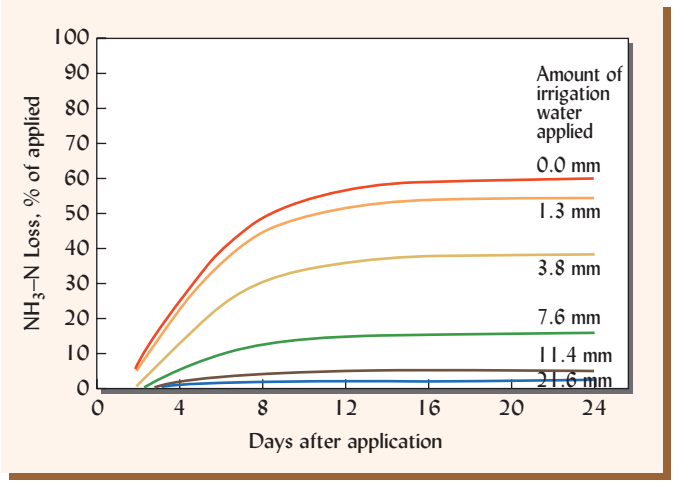

Figure 13.7 *Irrigation or rain water can wash surface applied fertilizer into the soil and greatly diminish losses to the atmosphere of nitrogen as NH_3 gas. In the research depicted here, 112 kg N/ha as urea fertilizer (H_2N–C–NH_2) was broadcast on the surface of an Adkins fine sandy loam (Xeric Haplocalcid) in eastern Oregon. The pH of the soil was 6.5, and that of the irrigation water was 7.8. Without the addition of irrigation water, 60% of the applied N was lost as NH_3 gas within two weeks of fertilization. The application of only 7.6 mm of water reduced the loss to 17% of that applied.* [Redrawn from Holcomb et al. (2011)]

Volatilization from Wetlands. Gaseous ammonia loss from nitrogen fertilizers applied to the surface of fishponds and flooded rice paddies can also be appreciable, even on slightly acid soils. The applied fertilizer stimulates algae growing in the paddy water. As the algae photosynthesize, they extract CO_2 from the water and reduce the amount of carbonic acid formed. As a result, the pH of the paddy water increases markedly, especially during daylight hours, to levels commonly above 9.0. At these pH levels, NH_3 gas is released from ammonium compounds and goes directly into the atmosphere. As with upland soils, this loss can be reduced significantly if the fertilizer is placed below the soil surface. Natural wetlands lose NH_3 gas by a similar daily cycle.

Ammonia Absorption. By the reverse of the ammonium loss mechanism just described, both soils and plants can absorb ammonia from the atmosphere. Thus the soil–plant system can help cleanse ammonia from the air, while deriving usable nitrogen for plants and soil microbes. In the Rocky Mountain region of the United States, NH_3 gas carried by wind from fertilized cropland and cattle feedlots has been shown to provide significant amounts of nitrogen to forests on mountain slope hundreds of kilometers away.

13.7 NITRIFICATION

As ammonium ions appear in the soil, they are generally oxidized quite rapidly by certain soil bacteria and archaea, yielding first nitrites and then nitrates. The prokaryotes that carry out this enzymatic oxidation are classed as **autotrophs** because they obtain their energy from oxidizing the ammonium ions rather than organic matter. The process termed **nitrification** (see Figure 13.3) consists of two main sequential steps. The first step results in the oxidation of ammonium to nitrite. Molecular research has shown that certain archaea (Crenarchaeota) may be active ammonia-oxidizing organisms in soils. In other soils, a specific group of autotrophic bacteria of the genus ***Nitrosomonas*** is thought to carry out most of the ammonia oxidation. In any case, the nitrite so formed is then immediately acted upon by a second group of autotrophs (the best known being the bacteria of the genus ***Nitrobacter***). Therefore, when NH_4^+ is released into the soil it is usually converted rapidly into NO_3^- (see Figure 13.8). The enzymatic oxidation releases energy and may be represented very simply as follows:

Step 1

$$\underset{\text{Ammonium}}{NH_4^+} + 1\tfrac{1}{2}O_2 \xrightarrow[\text{bacteria}]{\textit{Nitrosomonas}} \underset{\text{Nitrite}}{NO_2^-} + 2H^+ + H_2O + 275\text{ kJ energy} \qquad (13.4)$$

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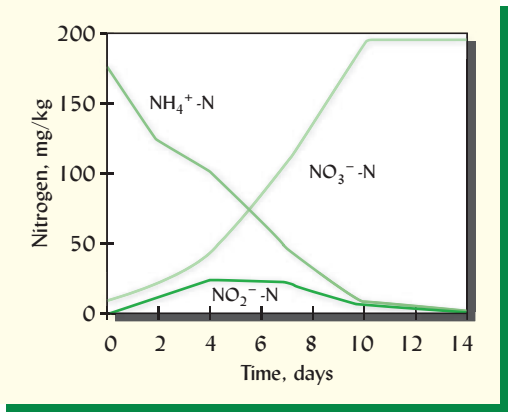
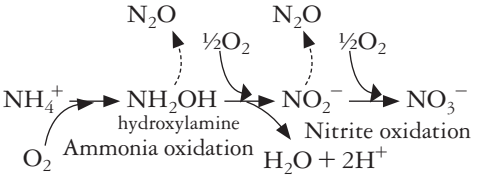


Figure 13.8 *Transformation of ammonium into nitrite and nitrate by nitrification. On day zero, the silt loam soil was amended with enough $(NH_4)_2SO_4$ to supply 170 mg of N/kg soil. It then underwent a warm, well-aerated incubation for 14 days. Every second day, soil samples were extracted and analyzed for various forms of nitrogen. Note that the increase in nitrate-N (NO_3^--N) almost mirrored the decline in ammonium-N (NH_4^+-N), except for the small amount of nitrite-N (NO_2^--N) that accumulated temporarily between day 2 and 10. This pattern is consistent with the two-step process depicted by Eqs. (13.4) and (13.5). No plants were grown during the study.* [Data selected from Khalil et al. (2004)]

Step 2

$$\underset{\text{Nitrite}}{NO_2^-} + {}^1\!/_2O_2 \xrightarrow[\text{bacteria}]{\textit{Nitrobacter}} \underset{\text{Nitrate}}{NO_3^-} + 76\text{ kJ energy} \tag{13.5}$$

So long as conditions are favorable for both reactions, the second transformation is thought to follow the first closely enough to prevent accumulation of much nitrite. This is fortunate, because even at concentrations of just a few mg/kg, nitrite is quite toxic to most plants. When oxygen supplies are marginal, the nitrifying bacteria may also produce some NO and N_2O, which are potent greenhouse gases (see Sections 12.9 and 13.8). The chemical reaction below (Eq. (13.6)), which combines steps 1 and 2, illustrates the production of hydroxylamine and possible production of N_2O gas between the initial oxidation of NH_4^+ and the production of nitrite and nitrate during nitrification



(13.6)

Regardless of the source of ammonium (i.e., ammonia-forming fertilizer, sewage sludge, animal excreta, or any other organic nitrogen source), nitrification will significantly increase soil acidity by producing H^+ ions, as shown in Reaction (13.6). See also Sections 9.6 and 13.14.

Soil Conditions Affecting Nitrification

The nitrifying bacteria are much more sensitive to environmental conditions than the broad groups of heterotrophic organisms responsible for the release of ammonium from organic nitrogen compounds (**ammonification**). Nitrification requires a supply of ammonium ions, but excess NH_4^+ can be toxic to *Nitrobacter*. The nitrifying organisms, being aerobic, require oxygen to make NO_2^- and NO_3^- ions and are therefore favored in well-drained soils. The optimum moisture for these organisms is about the same as that for most plants (about 60% of the pore space filled with water, Figure 13.9). Since they are autotrophs, their carbon sources are bicarbonates and CO_2. They perform best when temperatures are between 20 and 30 °C and perform very slowly if the soil is cold (below 5 °C).

Nitrification proceeds most rapidly where there is an abundance of exchangeable Ca^{2+} and Mg^{2+} and nutrient levels are optimum for the growth of higher plants. Nitrification is often constrained in soils high in smectite or allophane clays. These clays hold certain nitrogen-containing organic compounds in their intercolloid pores, thereby protecting them from microbial attack, including nitrification.

Nitrifying organisms are quite sensitive to some pesticides applied at high rates, but most studies suggest that at ordinary field rates, the majority of the pesticides have only a

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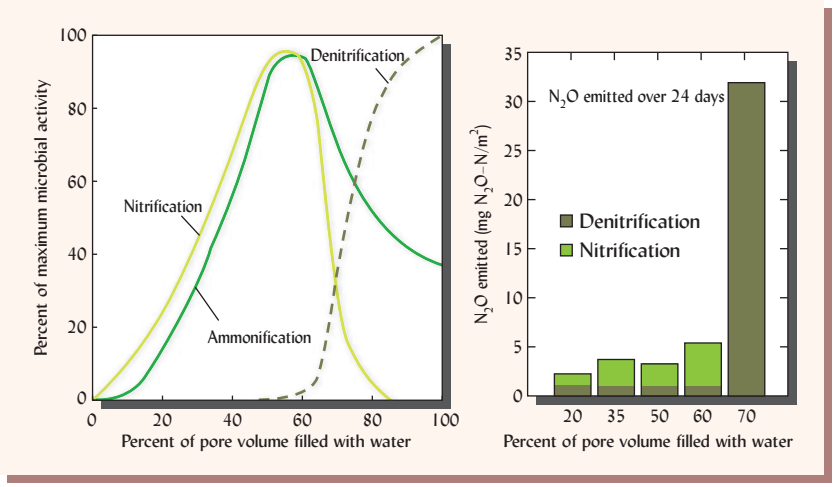

Figure 13.9 (Left) *Rates of nitrification, ammonification, and denitrification are closely related to the availability of oxygen and water as depicted by percentage of water-filled pore space. Both nitrification and ammonification proceed at their maximal rates near 55–60% water-filled pore space; however, ammonification proceeds in soils too waterlogged for active nitrification. Only a small overlap exists in the conditions suitable for nitrification and denitrification.* (Right) *Nitrous oxide (N_2O), is mainly produced by denitrification, but it is also a minor by-product of nitrification, with abrupt shift from one process to the other at water-filled porosities between 60 and 70%.* (Bar graph from Bateman and Baggs (2005))

minimal effect on nitrification. Agrochemical companies have marketed a number of compounds that can inhibit or slow down the nitrification process, thereby reducing the nitrate leaching potential. Such compounds, as well as others that retard the dissolution of urea, are discussed in Section 13.15.

Provided that all the preceding conditions are favorable, nitrification is such a rapid process that nitrate is generally the predominant mineral form of nitrogen in most soils. Irrigation of an initially dry arid-region soil, the first rains after a long dry season, the thawing and rapid warming of frozen soils in spring, and sudden aeration by tillage are examples of environmental fluctuations that typically cause a flush of soil nitrate production (Figure 13.10). The growth patterns of natural vegetation and the optimum planting dates for crops are greatly influenced by such seasonal changes in nitrate levels.

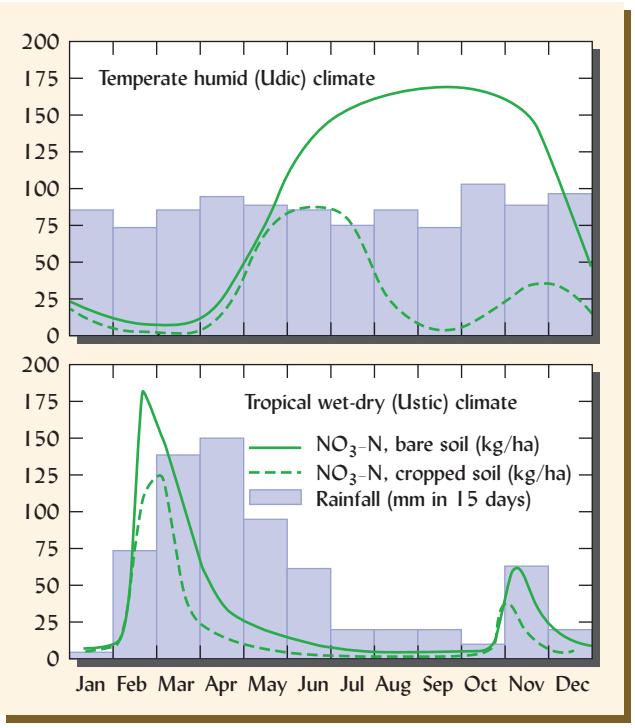

Figure 13.10 *Seasonal patterns of nitrate-N concentration in the A horizons of representative soils with and without growing plants.* (Upper) *In a representative northern hemisphere humid temperate region with cool winters and rainfall rather uniformly distributed throughout the year, NO_3^--N accumulates as the soil warms up in May and June. The nitrates are lost by leaching in the fall.* (Lower) *In a representative tropical region with four rainy months followed by eight months of dry, hot weather, a large flush of NO_3^--N appears when the rains first moisten the dry soil. This nitrate flush is caused by the rapid decomposition and mineralization of the dead cells of microorganisms previously killed by the dry, hot conditions. Note that soil nitrate is lower in both climates when plants are growing, because much of the nitrate formed is removed by plant uptake.* (Diagrams courtesy of Ray R. Weil)

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Several anaerobic microbial processes can in effect "reverse" nitrification. **Dissimilatory nitrate reduction to ammonium** is an anaerobic bacterial process that reduces NO_3^- to NO_2^- and then to NH_4^+. However, the best known and most common process that "reverses" nitrification is termed **denitrification**, an anaerobic process by which heterotrophic bacteria (or in some cases archaea or fungi) reduce nitrate to such gases as NO, N_2O, and N_2, as discussed next in Section 13.8.

13.8 GASEOUS LOSSES BY DENITRIFICATION AND ANAMMOX[7]

Denitrification

Nitrogen is commonly lost to the atmosphere when nitrate ions are converted to gaseous forms of nitrogen by a series of widely occurring biochemical reduction reactions termed **denitrification**.[8] The organisms that carry out this process are widespread and generally present in large numbers. They are mostly facultative anaerobic bacteria in genera such as *Pseudomonas*, *Bacillus*, *Micrococcus*, and *Achromobacter.* However certain archaea and fungi are also known to carry out denitrification. Most denitrifying organisms are *heterotrophs*, which obtain their energy and carbon from the oxidation of organic compounds. Other denitrifying bacteria are *autotrophs*, such as *Thiobacillus denitrificans*, which obtain their energy from the oxidation of sulfide. The exact mechanisms vary depending on the conditions and organisms involved. In the reaction, NO_3^- [N(V)] is reduced in a series of steps to NO_2^- [N(III)], and then to nitrogen gases that include NO [N(II)], N_2O [N(I)], and eventually N_2 [N(0)]:

$$\underset{\substack{\text{Nitrate ions}\\(+5)}}{2NO_3^-} \xrightarrow{-2O} \underset{\substack{\text{Nitrite ions}\\(+3)}}{2NO_2^-} \xrightarrow{-2O} \underset{\substack{\text{Nitric oxide gas}\\(+2)}}{2NO\uparrow} \xrightarrow{-O} \underset{\substack{\text{Nitrous oxide gas}\\(+1)}}{N_2O\uparrow} \xrightarrow{-O} \underset{\substack{\text{Dinitrogen gas}\\(0)}}{N_2\uparrow} \qquad (13.7)$$

Valence state of nitrogen

Although not shown in the simplified reaction given here, the oxygen released at each step would be used to form CO_2 from organic carbon (or SO_4^{2-} from sulfides if *Thiobacillus* is the nitrifying organism).

For these reactions to take place, sources of organic residues should be available to provide the energy the denitrifiers need. The soil air in the microsites where denitrification occurs should contain no more than 10% oxygen, and lower levels of oxygen are preferred. Optimum temperatures for denitrification are from 25 to 35 °C, but the process will occur between 2 and 50 °C. Very strong acidity ($pH < 5.0$) inhibits rapid denitrification and favors the formation of N_2O.

Generally, when oxygen levels are very low, the end product released from the overall denitrification process is dinitrogen gas (N_2). It should be noted, however, that NO and N_2O are commonly also released during denitrification (Figure 13.11), especially under the fluctuating aeration conditions that often occur in the field. The proportion of the three main gaseous products seems to be dependent mainly on the degree of oxygen depletion, as well as the prevalent pH, temperature, and concentrations of nitrate and nitrite ions available. For example, release of nitrous oxide (N_2O) is favored over dinitrogen gas (N_2) if soil pH is acidic, carbon supply is relatively low, the soil is not overly wet (some O_2 is present) and the concentrations of nitrite and nitrate are high (see Figures 13.9 and 7.13). Under very acid conditions, almost all of the loss occurs in the form of N_2O. Nitric oxide (NO) formation is generally quite small.

Codenitrification

Codenitrification is a related microbial process by which nitrite (NO_2^-) in the soil solution is reduced to N_2O and N_2 gases by such nitrogen compounds as ammonium (NH_4) or hydroxylamine (NH_2OH). Codenitrification is carried out by bacteria (e.g., *Streptomyces* spp.) and fungi

[7]For a review of recently revealed N cycle pathways of importance in ecosystems see Thamdrup (2012).

[8]Nitrate can also be reduced to nitrite and to nitrous oxide gas by nonbiological chemical reaction and under some circumstances by nitrifier bacteria, but these reactions are relatively minor in comparison with biological denitrification.

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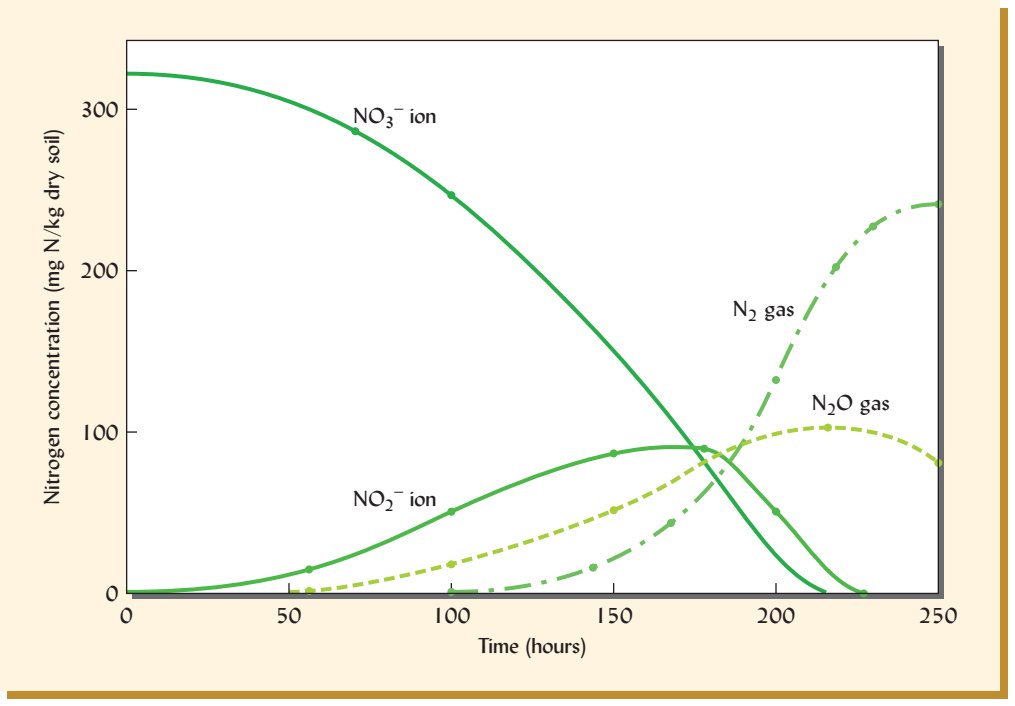

Figure 13.11 Changes in various forms of nitrogen during the process of denitrification in a moist soil incubated in the absence of atmospheric oxygen. [From Leffelaar and Wessel (1988)]

(e.g., *Fusarium oxysporum*) and has been measured in various aerobic soils, including those in agroecosystems and grasslands. In fact, fungal codenitrification may be the main source of N_2 emissions from grassland soils.

Anammox[9]

A more recently discovered bacterial process, the **anaerobic oxidation of ammonium** (***anammox***), converts ammonium to N_2 gas using nitrite as an electron acceptor. The nitrite required for this reaction may come from nitrifying bacteria or archaea that carry out aerobic ammonium oxidation as described in Section 13.6:

$$NH_4^+ + 1\tfrac{1}{2}O_2 \rightarrow NO_2^- + 2H^+ + H_2O \quad \text{(aerobic)} \tag{13.4}$$

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O \quad \text{(anaerobic)} \tag{13.8}$$

$$2NH_4^+ + 1\tfrac{1}{2}O_2 \rightarrow N_2 + 2H^+ + 3H_2O \quad \text{(combined net anammox reaction)} \tag{13.9}$$

Anammox bacteria are a very unusual group of organisms within the phylum Planctomycetes; in addition to cellular properties typical for bacteria, they also appear to have some features more typical of archaea and fungi. Their carbon source for growth is CO_2 and therefore a supply of organic carbon is not required for anammox to occur.

Although originally thought to be of widespread importance only in ocean water, sediments, and hydric soils, recent evidence suggests this reaction is also important in many (but not all) upland soils as well, so long as boundary conditions exist between aerobic and anaerobic environments. As suggested by the anammox equations above, the process requires the presence of linked oxidizing and reducing environments and typically occurs in redox transition zones such as the upper layers of saturated soils, the capillary fringe above the water table, the rhizosphere of plant roots, or the interior of macroaggregates in moderately wet soils (see Figure 7.10).

[9]For a review of the unique characteristics of anammox reactions and bacteria see van Niftrik and Jetten (2012).

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Atmospheric Pollution and Greenhouse Gas Emissions

Denitrification and anammox processes are ecologically important both because of the removal of nitrogen from an ecosystem, and because of the nitrogen gases they emit into the atmosphere. Nitrogen losses from soil during even a brief period of denitrification can bring about serious nitrogen deficiency in plants (Figure 13.12), while losses from nitrogen-laden groundwater or surface water can markedly improve the water quality. Dinitrogen (N_2) gas is quite inert and environmentally harmless, but the oxides of nitrogen are very reactive gases and have the potential to do serious environmental damage in at least four ways. First, when N_2O rises into the upper atmosphere, it contributes to climate change and global warming by absorbing infrared radiation (as much as 300 times the effect of an equal amount of CO_2) that would otherwise escape into space (see Section 12.9). Second, the nitrogen oxide gases can react with volatile organic pollutants to form ground-level ozone, a major air pollutant in the photochemical smog that plagues many urban areas. Third, NO and N_2O released into the atmosphere by denitrification can contribute to the formation of nitric acid, one of the principal components of acid rain.

Finally, as N_2O moves up into the stratosphere, it may participate in reactions that result in the destruction of ozone (O_3), a gas that helps shield the Earth from harmful ultraviolet solar radiation. In recent decades this protective ozone layer has been measurably depleted by reaction with industrial chlorofluorocarbons as well as with N_2O and other gases. As this protective layer is further degraded, thousands of additional cases of skin cancer are likely to occur annually. While there are other important sources of N_2O, such as automobile exhaust fumes, a major contribution to the problem is being made by denitrification in soils, especially in rice paddies, wetlands, and heavily fertilized or manured agricultural soils.

Quantity of Nitrogen Lost Through Denitrification

As might be expected, the exact magnitude of denitrification loss is difficult to predict and will depend on management practices and soil conditions. Studies of forest ecosystems have shown that during periods of adequate soil moisture, denitrification results in a slow but relatively steady loss of nitrogen from these undisturbed natural systems. In contrast, most field measurements of gaseous nitrogen loss from agricultural soils reveal that the losses are highly variable in both time and space. The greater part of the annual nitrogen loss often occurs during just a few days in summer, when rain or irrigation water temporarily waterlog the warm, nitrogen-fertilized, carbon-rich soils (Figure 13.12).

Low-lying, organic-rich areas and other hot spots may lose nitrogen ten times as fast as the average rate for a typical field. Although as much as 10 kg/ha of nitrogen may be lost in a single day from the sudden saturation of a well-drained, humid-region soil, such soils rarely lose more than 5–15 kg N/ha annually by denitrification. But where aeration is restricted and

Figure 13.12 *Foliar symptoms indicate severe N deficiency in the corn growing on these well-fertilized, high organic matter Udolls in central Illinois, USA. Heavy rains during warm weather ponded water on the low-lying parts of the field resulting in perfect conditions for denitrification to cause large losses of nitrogen. Some leaching of nitrate and dissolved organic N undoubtedly also occurred.* (Photo courtesy of Ray R. Weil)

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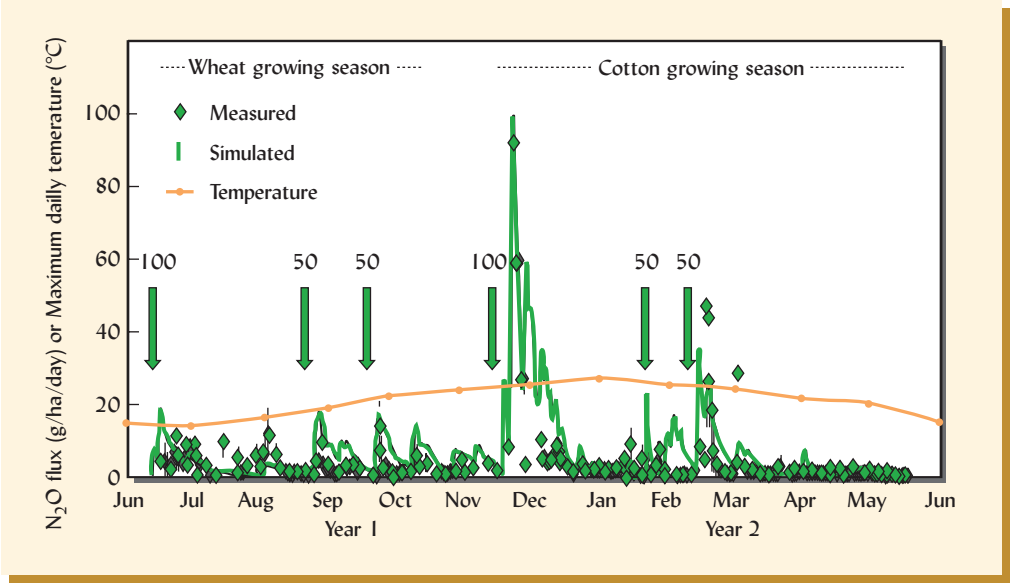

Figure 13.13 *The episodic nature of N_2O gas emissions from microbial process such as denitrification in an agricultural soil. Most of the loss during the two-year period took place in just one month (December) when the soil was warm, a large amount of N had just been applied, the just-planted crop was not yet using much water and irrigation made the soil quite wet. The arrows indicate the timing and amount (kg N/ha) of N fertilizer applications to a two-year wheat–cotton crop sequence on a sprinkler-irrigated heavy clay Vertisol in Queensland, Australia. The data points (♦) indicate the actual measured fluxes of N_2O, a powerful greenhouse climate-forcing gas produced by denitrification. The solid green line is the N_2O flux calculated by DayCent, a computer model that simulates flows of carbon, nutrients, and trace gases between the atmosphere, soil, and plants. The amounts of N lost from the soil as molecular nitrogen (N_2) gas are not shown, but were 20–100 times as great as the N_2O losses. The orange data points (—●—) and line indicate the monthly maximum daily temperature (°C), with Australia's hot season occurring December–March.* [Graph redrawn from data in Scheer et al. (2014)]

large amounts of nitrogen fertilizer are applied, losses of 30–60 kg N/ha/yr of nitrogen have been observed (Figure 13.13).

Much of the nitrogen dissolved in water moving from watersheds into shallow streams and slow-moving rivers is lost by denitrification. As the water moves through these shallow transport channels, there is opportunity for the nitrogen to come in contact with the river bottoms where the denitrification occurs. Research suggests that 5–20% of the nitrogen in some streams or rivers may be lost by denitrification.

Denitrification in Flooded Soils

In flooded soils, such as those found in natural wetlands or rice paddies (Figure 13.14), losses by denitrification may be very high. The soils of rice paddies are commonly subject to alternate periods of wetting and drying. Nitrates that are produced by nitrification during the dry periods are often subject to denitrification when the soils are submerged. Even when submerged, the soil permits both reactions to take place at once—nitrification occurs at the soil–water interface where some oxygen derived from the water is present and denitrification occurs at lower soil depths (see Figure 13.15). Nonetheless, nitrogen losses from rice soils can be dramatically reduced by keeping the soil flooded and by deep placement of the fertilizer into the reduced zone of the soil. In this zone, because there is insufficient oxygen to allow nitrification to proceed, nitrogen remains in the ammonium form and is not susceptible to loss by denitrification.

The sequential combination of nitrification and denitrification also operates in natural and artificial wetlands. Tidal wetlands (see Figure 13.14*c*), which become alternately anaerobic and aerated as the water level rises and falls, have particularly high potentials for converting nitrogen to gaseous forms. Often the resulting rapid loss of nitrogen is considered to be a beneficial function of wetlands, in that the process protects estuaries and lakes from

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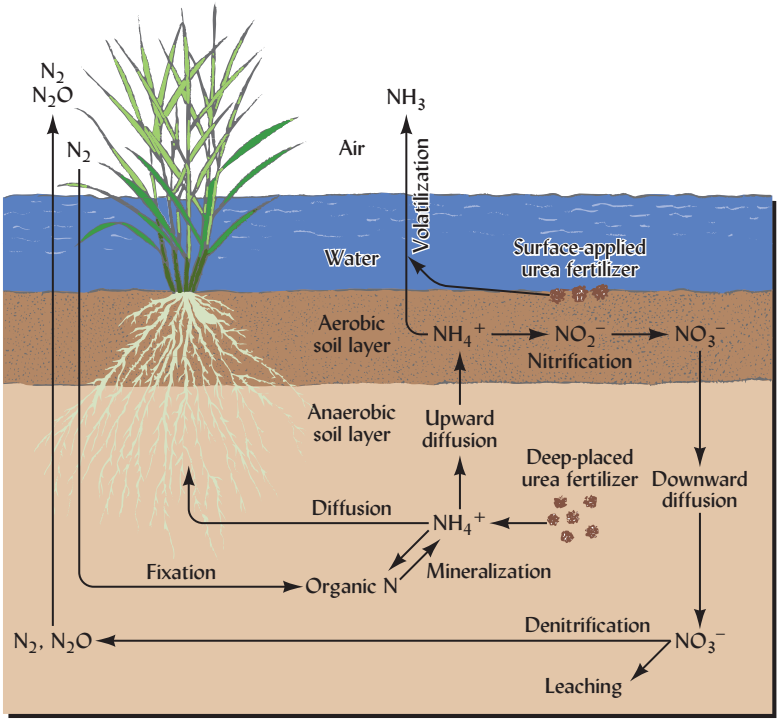
Figure 13.14 *Denitrification can be very efficient in removing nitrogen from flooded systems that combine aerobic and anaerobic zones and have a large supply of microbial available carbon. Examples of such systems include: (a) flooded rice paddies, (b) lagoons in which animal liquid manure is stored, (c) natural tidal marsh wetlands, and (d) constructed wetlands designed to remove nitrogen (and sediments) from urban storm water runoff.* (Photos courtesy of Ray R. Weil)

Figure 13.15 *Nitrification–denitrification reactions and dynamics of the related processes controlling nitrogen loss from the aerobic–anaerobic layers of a flooded soil system. Nitrates, which form in the thin aerobic soil layer just below the soil–water interface, diffuse into the anaerobic (reduced) soil layer below and are denitrified to the N_2 and N_2O gaseous forms, which are lost to the atmosphere. In the case of fertilized rice paddies, placing the urea or ammonium-containing fertilizers deep in the anaerobic layer prevents N oxidation of ammonium ions to nitrates, thereby greatly reducing N loss.* [Modified from Patrick (1982)]



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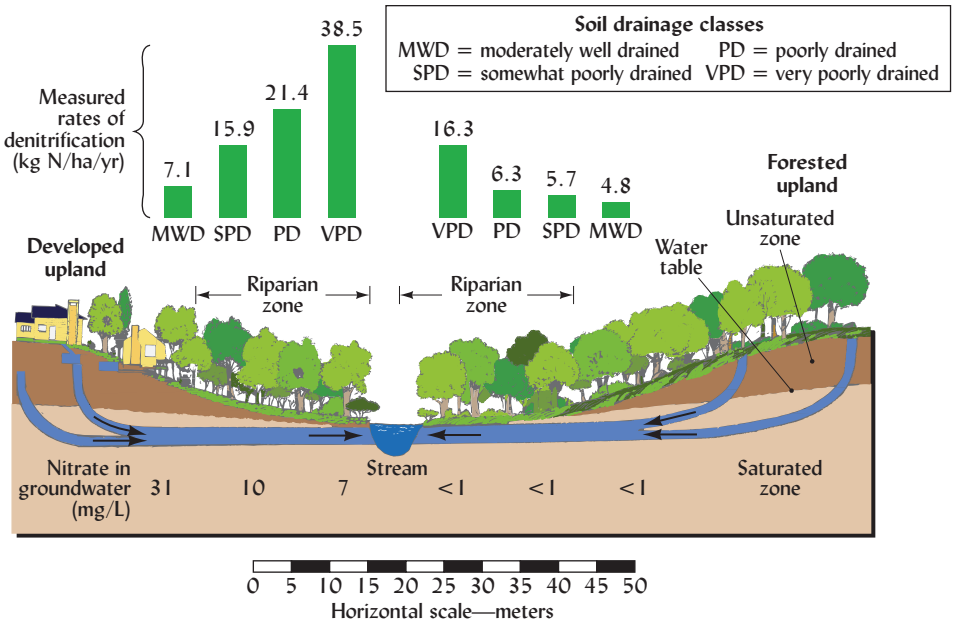

Figure 13.16 *Denitrification in riparian wetlands receiving groundwater with high- and low-nitrate contents. The high-nitrate groundwater (left) came from houses using septic drainfields (see Section 6.8). The low-nitrate groundwater (right) came from undeveloped forest. Riparian zones on both sides of the stream had red maple–dominated forest. After entering the riparian wetland, the nitrate content of the contaminated groundwater was reduced by 75%, from 31 to 7 mg/L nitrate. The soils in this study site are very sandy Inceptisols and Entisols. In other regions, riparian zones with finer-textured soils have shown even more complete nitrate removal.* [Diagram courtesy of Ray R. Weil Data from Hanson et al. (1994)]

the eutrophying effects of too much nitrogen (see Section 13.9). In fact, wastewater high in organic carbon and nitrogen can be cleaned up quite efficiently by allowing it to flow slowly over or through a specially designed water-saturated soil system such as stormwater retention wetlands (see Figure 13.14*d*) or overland flow wastewater treatment systems.

Denitrification in Groundwater

In many cases studied, contaminated groundwater loses most of its nitrate nitrogen load as it flows through the **riparian** zone on its way to the stream. The apparent removal of nitrate may be quite dramatic, whether the nitrate source is suburban septic drainfields (Figure 13.16), livestock feeding operations, or fertilized cropland. Most of nitrate is believed to be lost by denitrification, stimulated by organic compounds leached from the decomposing forest litter and by the anaerobic conditions that prevail in the wet riparian zone soils.

Constructed wetlands can be used to reduce the nitrate content of surface waters moving toward streams. When coupled with buffer strips, such wetlands can remove half or more of the nitrates of the surface water before it enters the stream channel (see Figure 13.17).

We have just discussed a number of biological processes (e.g., nitrate leaching, ammonia volatilization, N_2 production by denitrification) that lead to loss of nitrogen from the soil system. Were such losses not matched by N inputs, ecosystems would have long ago run out of reactive N and life in them would have ground to halt. To understand why such a dire situation has not come to pass, we turn our attention next to the principal biological process by which soil nitrogen is replenished.

13.9 BIOLOGICAL NITROGEN FIXATION

Next to plant photosynthesis, **biological nitrogen fixation** is probably the most important biochemical reaction for life on Earth. This process converts the inert dinitrogen gas of the atmosphere (N_2) to reactive nitrogen that becomes available to all forms of life through the nitrogen cycle. The process is carried out by a limited number of bacteria, including several species of *Rhizobium*, actinomycetes, and cyanobacteria (formerly termed blue-green algae).

Globally, enormous amounts of nitrogen are fixed biologically each year. Terrestrial systems alone fix an estimated 139 million Mg. However, the amount that is fixed in the manufacture of fertilizers is now nearly as great (see Figure 13.18).

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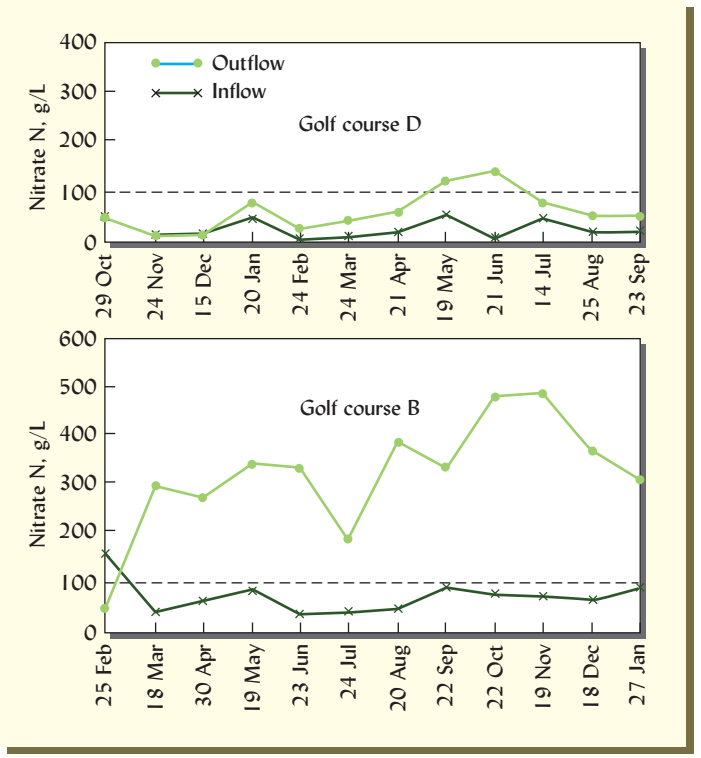

Figure 13.17 *Monthly levels of nitrate-N in streams entering (inflow) and leaving (outflow) two golf courses in North Carolina, USA. Note the very high levels of nitrate in the outflow from Course B, far in excess of the 100 μg level that is known to encourage undesirable phytoplankton blooms in coastal waters (dotted line). The much lower levels flowing out of Course D are thought to be due to two ponds, through which the water passes, and to a forested wetland along the edge of the course. Such data suggest that golf courses can be significant sources of nitrate losses into streams, but that this is subject to managerial control.* [Redrawn from Mallin and Wheeler (2000)]

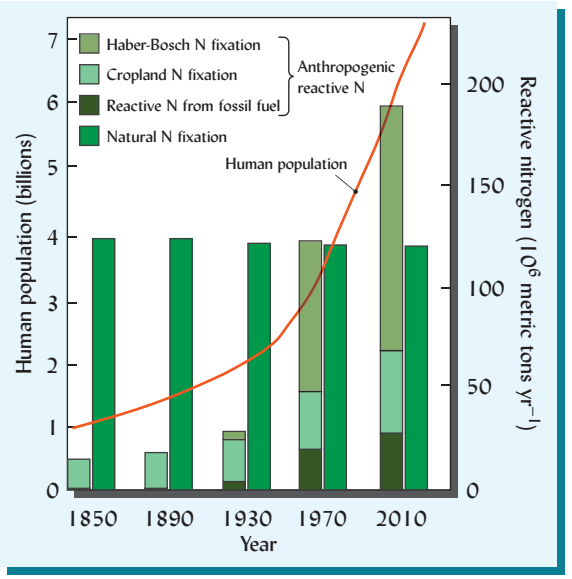

Figure 13.18 *Changes in the human population and its contribution to global reactive nitrogen. Note that by the early 1980s human-caused N fixation (industrial fertilizer production, agricultural crop legumes, and combustion of fossil fuels) had surpassed natural N fixation (by legumes, cyanobacteria, and actinomycetes in natural terrestrial ecosystems as well as by lightning).* [Based on data in Lambert and Driscoll (2003) and Galloway and Cowling (2002)]

The Mechanism. Regardless of the organisms involved, the key to biological nitrogen fixation is the enzyme *nitrogenase*, which catalyzes the reduction of dinitrogen gas to ammonia

$$N_2 + 8H^+ + 6e^- \xrightarrow[\text{(Fe,Mo)}]{\text{(Nitrogenase)}} 2NH_3 + H_2 \qquad (13.10)$$

The ammonia, in turn, is combined with organic acids to form amino acids and, ultimately, proteins

$$NH_3 + \text{organic acids} \longrightarrow \text{amino acids} \longrightarrow \text{proteins} \qquad (13.11)$$

The site of N_2 reduction is the enzyme **nitrogenase**, a complex consisting of two proteins, the smaller of which contains iron while the larger contains molybdenum, sulfur, and

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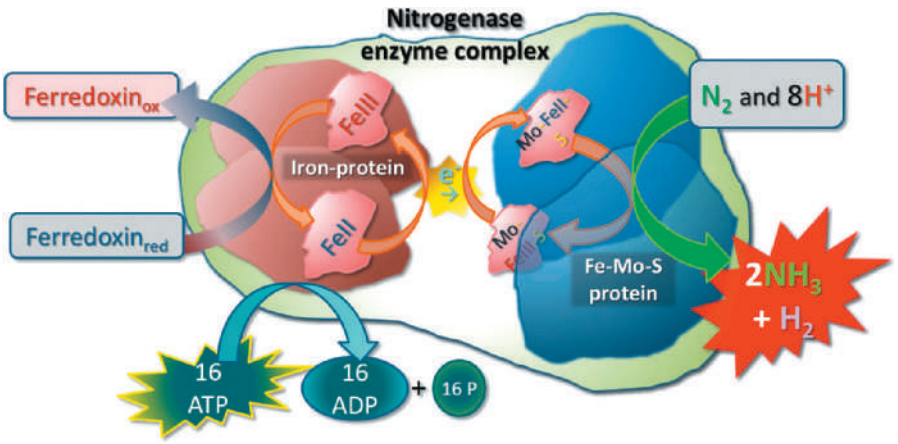

Figure 13.19 *The nitrogenase complex consists of two proteins. The larger protein (right) converts atmospheric N_2 to NH_3 using electrons provided by the smaller protein (left). Energy-rich hydrogen gas (H_2) may also be produced. Energy from ATP conversion to ADP along with electrons from ferrodoxin reduce the FeIII in the smaller iron–protein. Meanwhile, the molybdenum–iron–sulfur clusters in the large protein capture nitrogen (N_2) from the air, while the Fe in the clusters receives the electrons (e^-) provided by the small protein so that N_2 can be reduced to NH_3. Nitrogen fixation in nature may be limited by insufficient supplies of S, Fe, Mo, or P.* (Diagram courtesy of Ray R. Weil)

iron (Figure 13.19). Several salient facts about this enzyme and its function are worth noting, for nitrogenase is unique and its role in the nitrogen cycle is of great importance to humankind.

1. Breaking the strong N≡N triple bond in N_2 gas requires a great deal of energy. Therefore, this microbial process is greatly enhanced when it is carried out in association with plants, which can supply energy from photosynthesis.
2. Nitrogenase is destroyed by free O_2, so organisms that fix nitrogen must protect the enzyme from exposure to oxygen. When nitrogen fixation takes place in root nodules (see Section 13.11), one means of protecting the enzyme from free oxygen is the formation of *leghemoglobin.* This compound, which gives actively fixing nodules a red interior color, binds oxygen in such a way as to protect the nitrogenase while making oxygen available for respiration in other parts of the nodule tissue. Leghemoglobin is virtually the same molecule as the hemoglobin that gives human blood its red color while carrying oxygen to our body cells.
3. The reduction reaction is end-product inhibited—for example, an accumulation of ammonia will inhibit nitrogen fixation. Also, too much nitrate in the soil will inhibit the formation of nodules (see Section 13.11).
4. Nitrogen-fixing organisms have a relatively high requirement for molybdenum, iron, phosphorus, and sulfur, because these nutrients are part of the nitrogenase molecule and also needed for its synthesis and use.

Fixation Systems. Biological nitrogen fixation occurs through a number of microbial systems that may or may not be directly or indirectly associated with plants (Table 13.2). Although the legume–bacteria symbiotic systems have received the most attention, the other systems involve many more families of plants worldwide and may supply large amounts of biologically fixed nitrogen to the soil. Each major system will be discussed briefly.

13.10 SYMBIOTIC FIXATION WITH LEGUMES

Plants of the legume family (Fabaceae) are famous for their distinctive ability to provide the major biological source of fixed nitrogen in agricultural soils. They do so in association with several genera of bacteria (in the subclass Alpha-Proteobacteria) collectively termed **rhizobial bacteria**. These bacteria include species in the genera *Rhizobium*, *Mesorhizobium*, *Bradyrhizobium*, and *Ensifer*. The legume plants and rhizobial bacteria form a **symbiosis** (a mutually beneficial relationship) in which the host plant supplies the bacteria with carbohydrates for energy, and the bacteria reciprocate by supplying the plant with reactive nitrogen with which to make essential plant compounds such as proteins and chlorophyll. In a complex biochemical "conversation" involving many specific signaling compounds, the rhizobial bacteria find and infect the legume plant root hairs and colonize the cortical cells. Here the rhizobial bacteria ultimately induce the formation of **root nodules** that serve as the site of nitrogen fixation (Figure 13.20).

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Table 13.2
INFORMATION ON DIFFERENT SYSTEMS OF BIOLOGICAL NITROGEN FIXATION

N-fixing systems	Organisms involved	Plants involved	Site of fixation
Symbiotic			
Obligatory			
Legumes	Rhizobial bacteria *Rhizobia*, *Bradyrhizobia*, *others*	Legumes (Fabaceae)	Root nodules, stem nodules
Nonlegumes (angiosperms)	Actinomycetes bacteria (*Frankia*)	Nonlegume angiosperms (Betulaceae, Casuarinaceae and Myricaceae, Rosaceae, Eleagnaceae, Rhamnaceae, Datiscaceae and Coriariaceae)	Root nodules
Associative			
Symbiotic	Cyanobacteria	Various species of Angiosperms (flowering plants), Gymnosperms (conifers), Pteridophytes (ferns, *Azolla*), and Bryophytes (mosses, liverworts)	Stem glands, leaf and root nodules, special leaf cavities, gametophyte cavities, or root environment
	Plant growth-promoting rhizobacteria (PGPR)	Many families of plants, including Poaceae (grasses, rice, corn).	Root environment
Nonsymbiotic		Not involved with plants	Soil, water independent of plants

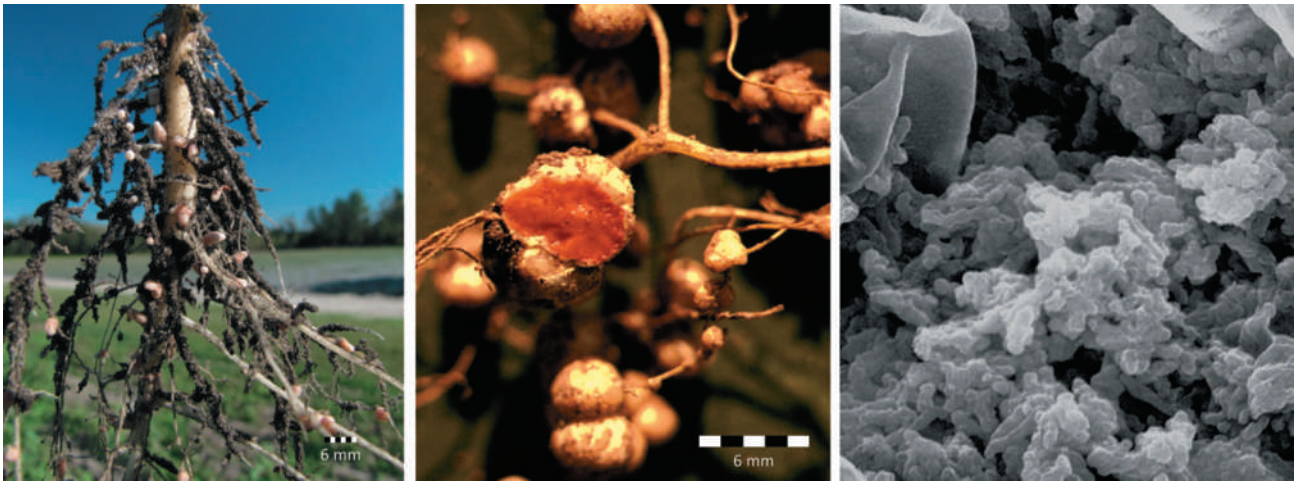

Figure 13.20 *Photos illustrating nodules on legume roots. In (a) the nodules are seen on the roots of a sunn hemp plant (Crotalaria juncea), used as a cover crop to add N to soils. In (b) a close-up shows a few nodules on roots of a soybean plant with one nodule sliced open to expose the red color of its oxygenated leghemoglobin. A scanning electron micrograph (c) shows a single plant cell within a soybean nodule stuffed with the* Bradyrhizobium japonicum *bacteria specific to the symbiosis with soybean.* (Color photos courtesy of Ray R. Weil; SEM courtesy of W. J. Brill, University of Wisconsin)

Organisms Involved. A given rhizobial bacteria species will infect some legumes but not others. For example, *Rhizobium trifolii* inoculates *Trifolium* species (most clovers), but not sweet clover, which is in the genus *Melilotus.* Likewise, *Rhizobium phaseoli* inoculates *Phaseolus vulgaris* (beans), but not soybeans, which are in the genus *Glycine.* This specificity of interaction is one basis for classifying rhizobia (see Table 13.3). Legumes that can be inoculated by a given *Rhizobium* species are included in the same **cross-inoculation group**.

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Table 13.3
CLASSIFICATION OF RHIZOBIA BACTERIA AND ASSOCIATED LEGUME CROSS-INOCULATION GROUPS
The genera Rhizobium *and* Ensifer *contain fast-growing, acid-producing bacteria, while those of* Bradyrhizobium *are slow growers that do not produce acid.*

Bacteria		
Genus	**Species/subgroup**	**Host legume**
Ensifer	*E. meliloti*	*Melilotus* (sweet clovers), *Medicago* (alfalfa), *Trigonella* spp. (fenugreek)
Rhizobium	*R. leguminosarum*	
	bv. *viceae*	*Vicia* spp. (vetches), *Pisum* (peas), *Lens* (lentils), *Lathyrus* (sweet pea), *Vicia faba* (faba bean)
	bv. *trifolii*	*Trifolium* spp. (most clovers)
	bv. *phaseoli*	*Phaseolus* spp. (dry bean, string bean, etc.)
	R. Fredii	*Glycine* spp. (e.g., soybean)
	R. spp.	*Securigera varia* (crown vetch)
	R. spp.	Trees in Leucaena group: *Leucaena* spp. *Sesbania grandiflora; Calliandra calothyrsus; Gliricidia sepium; Prosopis* spp.
	R. lupini	*Lupinus* spp. (lupins)
Bradyrhizobium	*B. japonicum*	*Glycine* spp. (e.g., soybean)
	B. spp.	*Vigna* (cowpeas, mung bean), *Arachis* (peanut), *Cajanus* (pigeon pea), *Pueraria* (kudzu), *Crotalaria* (crotalaria), and many other tropical legumes; *Phaseolus lunatus* (lima bean) *Acacia* spp. (acacia trees), *Desmodium* spp., *Stylosanthes* spp., *Centrosema* sp., *Psophocarpus tetragonolobus* (winged bean), *Lablab purpureus* (Lablab bean), *Pueraria phaseoloides*
Mesorhizobium	*M. loti*	*Lotus* (trefoils), *Lupinus* (lupins), *Cicer* (chickpea), *Anthyllis*, *Leucaena*, and many other tropical trees
Azorhizobium	*A. spp.*	Produces stem nodules on *Sesbania rostrata*

In soils which have grown a given legume for several years, the appropriate species of rhizobial bacteria is probably present. Often, however, the natural rhizobial population in the soil is too low or the strain of the rhizobial bacteria species present is not effective (Figure 13.21). In such circumstances, special mixtures of the appropriate rhizobial bacteria may be applied as an **inoculant**, either by coating the legume seeds or by applying the inoculant directly to the soil. Effective and competitive strains of rhizobial bacteria are available commercially, and often give significant yield increases if used on the proper crops. You may want to refer to Table 13.3 when planting legume plants or purchasing commercial inoculant. Always check the inoculant label to be sure it will work for the intended plant species.

Quantity of Nitrogen Fixed. The rate of biological fixation is greatly dependent on soil and climatic conditions. The legume–*Rhizobium* associations generally function best on soils that are not too acid (although *Bradyrhizobium* associations generally can tolerate considerable acidity) and that are well supplied with essential nutrients. However, high levels of available nitrogen, whether from the soil or added in fertilizers, tend to depress biological nitrogen fixation (Figure 13.22). Apparently, plants make the heavy energy investment required for symbiotic nitrogen fixation only when supplies of mineral nitrogen from the soil are quite limited.

Although quite variable from site to site, the amount of nitrogen biologically fixed can be quite high, especially for those systems involving nodules, which supply energy from photosynthates and protect the nitrogenase enzyme system (Table 13.4). Nonnodulating or nonsymbiotic systems generally fix relatively small amounts of nitrogen. Nonetheless, many natural plant communities and agricultural systems (generally involving legumes) derive the bulk of their nitrogen needs from biological fixation.

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Figure 13.21 *This soybean crop in East Africa was a total failure. The soybean seeds were not inoculated with the proper bacteria prior to planting in a field that had been newly cleared from forest vegetation and had never grown soybeans before.* (Photo courtesy of Ray R. Weil)

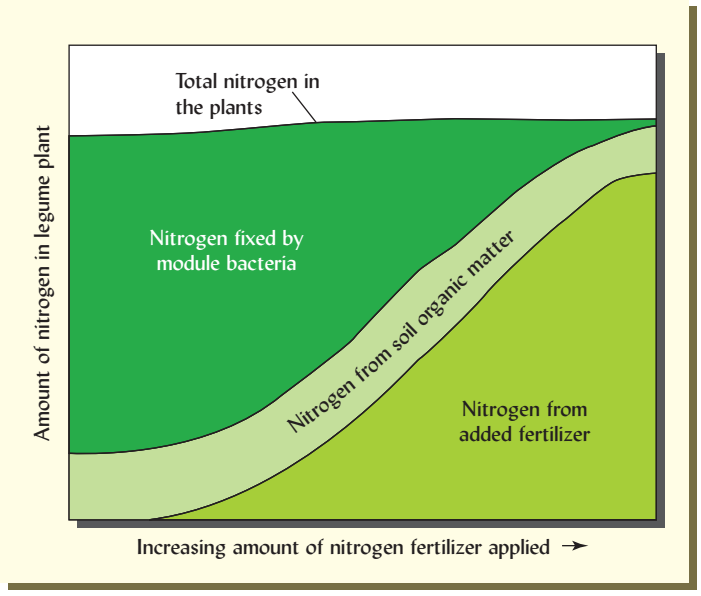

Figure 13.22 *Influence of adding inorganic nitrogen on the nitrogen found in a representative legume plant. As more nitrogen fertilizer is added, the plant obtains less of its nitrogen by biological fixation. The inorganic nitrogen merely replaces biologically fixed N, saving the plant some energy that would have been allocated to the nodule bacteria. Plant growth (not shown) is also little affected by the fertilizer application. However, some legume species fix nitrogen so inefficiently (e.g.,* Phaseolus *bean) that they are more likely to respond positively to the use of nitrogen fertilizer. The uptake of inorganic nitrogen released by mineralization (middle pool in diagram) may or may not be much affected by the fertilizer.* (Diagram courtesy of Ray R. Weil)

Effect on Soil Nitrogen Level. Over time, the presence of nitrogen-fixing species can significantly increase the nitrogen content of the soil and benefit nonfixing species grown in association with fixing species (see Figure 13.23).

Although some direct transfer may take place via mycorrhizal hyphae connecting two plants, most of the transfer results from mineralization of nitrogen-rich compounds in root exudates and in sloughed-off root and nodule tissues. Ammonium and nitrate thus released into the soil are available to any plant growing in association with the legume. The vigorous development of a grass in a legume–grass mixture is evidence of this rapid release (Figure 13.24), as are the relatively high nitrate concentrations sometimes measured in groundwater under legume crops. Some legumes are relatively weak nitrogen fixers so most of the nitrogen they absorb must come from the soil. Consequently, it should not be assumed that the symbiotic systems always increase soil nitrogen. Only in cases where the soil is low in available nitrogen and vegetation includes strong nitrogen fixers would this be likely to be true.

In the case of legume crops harvested for seed or hay, most of the nitrogen fixed is removed from the field with the harvest. Nitrogen additions from such crops should be considered as nitrogen *savers* for the soil rather than nitrogen builders. On the other hand, considerable buildup of soil nitrogen can be achieved by perennial legumes (such as alfalfa or kudzu) and by annual legumes (such as hairy vetch) if the entire growth is returned to the soil as **green manure**. If managed to maximize the return of their high-nitrogen biomass, legume

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Table 13.4
TYPICAL LEVELS OF NITROGEN FIXATION FROM DIFFERENT SYSTEMS

Crop or plant	Associated organism	Typical levels of nitrogen fixation, kg N/ha/yr
Symbiotic		
Legumes (nodulated)		
Ipil-ipil tree (*Leucaena leucocephala*)	Bacteria (*Rhizobium*)	100–500
Locust tree (*Robina* spp.)		75–200
Alfalfa (*Medicago sativa*)		150–250
Clover (*Trifolium pratense L.*)		100–150
Lupine (*Lupinus*)		50–100
Vetch (*Vicia villosa*)		50–150
Bean (*Phaseolus vulgaris*)		30–50
Cowpea (*Vigna unguiculata*)	Bacteria (*Bradyrhizobium*)	50–100
Peanut (*Arachis*)		40–80
Soybean (*Glycine max L.*)		50–150
Pigeon pea (*Cajanus*)		150–280
Kudzu (*Pueraria*)		100–140
Nonlegumes (nodulated)		
Alders (Alnus)	Actinomycetes (*Frankia*)	25–150
Ironwoods (Casuarina)		10–20
Species of Gunnera	Cyanobacteria[a] (*Nostoc*)	10–20
Nonlegumes (nonnodulated)		
Pangola grass (*Digitaria decumbens*)	Bacteria (*Azospirillum*)	5–30
Bahia grass (*Paspalum notatum*)	Bacteria (*Azobacter*)	5–30
Azolla	Cyanobacteria[a] (*Anabaena*)	150–300
Nonsymbiotic	Bacteria (*Azobacter, Clostridium*)	5–20
	Cyanobacteria[a] (various)	10–50

Note: [a]Formerly referred to as *blue-green algae.*

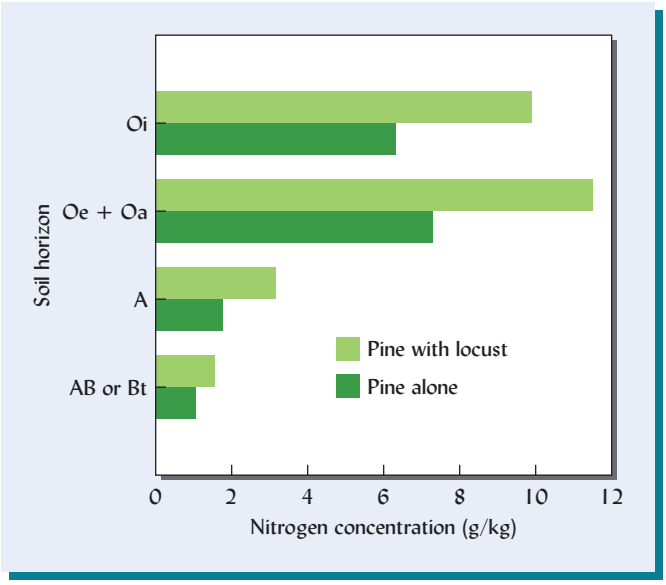

Figure 13.23 *Nitrogen concentrations in forest soil horizons showing the effects of New Mexican locust trees (Robinia neomexicana) growing in association with ponderosa pine (Pinus ponderosa) in a region of Arizona, USA, receiving about 670 mm of rainfall per year. The data are means from 20 stands of pondersosa pine, half of them with the nitrogen-fixing legume trees (locust) in the understory. The soils are Eutrustalfs and Argiustolls with loam and clay loam textures.* (Data from Klemmedson (1994))

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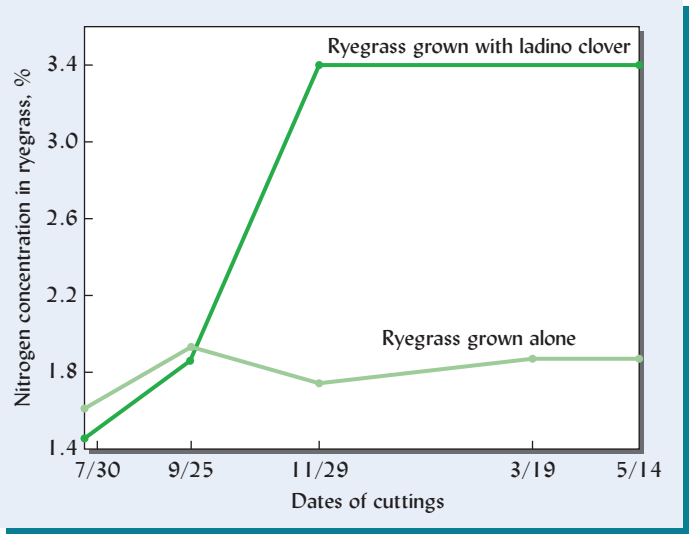

Figure 13.24 *Nitrogen concentrations of five field cuttings of ryegrass grown alone or with ladino clover. For the first two harvests, nitrogen fixed by the clover was not available to the ryegrass, and the nitrogen concentration of the ryegrass forage was low. In subsequent harvests, the fixed nitrogen apparently was available and was taken up by the ryegrass. This was probably due to the mineralization of dead ladino clover root tissue.* (From Broadbent et al. (1982))

green manures can be used to replace most or even all of the nitrogen fertilizer typically used in certain crop rotations. In any case, the nitrogen contributions from legumes should be taken into account when estimating nitrogen fertilizer needs for maximum plant production with minimal environmental pollution (Section 13.15).

13.11 SYMBIOTIC FIXATION WITH NONLEGUMES[10]

Nodule-Forming Nonlegumes

Some 220 species from eight plant families are known to develop nodules and to accommodate symbiotic nitrogen fixation when their root hairs are invaded by soil actinomycetes of the genus *Frankia.* Most of these *actinorhizal* plants are woody shrubs and trees that form distinctive nodules (Figure 13.25, *inset*). Table 13.5 lists several of the more important actinorhizal in certain forests and wetlands.

The rates of nitrogen fixation per hectare compare favorably with those of the legume–*Rhizobium* associations (see Table 13.4). On a worldwide basis, the total nitrogen fixed in this way may even exceed that fixed by agricultural legumes. Because of their nitrogen-fixing ability, certain of the tree–actinomycete associations are able to colonize infertile soils and newly forming soils on disturbed lands, which may have extremely low fertility as well as other conditions that limit plant growth (Figure 13.25). Once nitrogen-fixing plants become established and begin to build up the soil nitrogen supply through leaf litter and root exudation, the land becomes more hospitable for colonization by other species. *Frankia* thus play a very important role in the nitrogen economy of areas undergoing succession, as well as in established wetland forests.

Certain cyanobacteria are known to develop nitrogen-fixing symbiotic relations with green plants. One involves nodule formation on the stems of *Gunnera*, an angiosperm common in marshy areas of the southern hemisphere. In this association, cyanobacteria of the genus *Nostoc* fix 10–20 kg N/ha/yr (see Table 13.4).

Symbiotic Nitrogen Fixation Without Nodules

Among the most significant nonnodule nitrogen-fixing systems are those involving cyanobacteria. One system of considerable practical importance is the *Azolla–Anabaena* complex, which flourishes in certain rice paddies of tropical and semitropical areas (Figure 13.26). The *Anabaena* cyanobacteria inhabit cavities in the leaves of the floating fern *Azolla* and fix quantities of nitrogen comparable to those of the more efficient *Rhizobium*–legume complexes (see Table 13.4).

[10]For a scientific review of microbial N fixation in association with nonleguminous plants, see Santi et al. (2013).

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Figure 13.25 *Soil actinomycetes of the genus* Frankia *can nodulate the roots of certain woody plant species and form a nitrogen-fixing symbiosis that rivals the legume–rhizobia partnership in efficiency. The actinomycete-filled root nodule (a) is the site of nitrogen fixation. The red alder tree (b) is among the first pioneer tree species to revegetate disturbed or badly eroded sites in high-rainfall areas of the Pacific Northwest in North America. This young alder is thriving despite the nitrogen-poor, eroded condition of the soil because it is not dependent on soil nitrogen for its needs.* (Photos courtesy of Ray R. Weil)

Table 13.5
MAJOR ACTINORHIZAL PLANTS: ACTINOMYCETE-NODULATED NONLEGUME ANGIOSPERMS
About 220 actinorhizal species are known as compared to some 13,000 legume species.

Genus	Family	Geographic distribution
Alnus	Betulaceae	Cool regions of the northern hemisphere
Ceanothus	Rhamnaceae	North America
Myrica	Myricaceae	Many tropical, subtropical, and temperate regions
Casuarina	Casuarinaceae	Tropics and subtropics
Elaeagnus	Elaeagnaceae	Asia, Europe, North America
Coriaria	Coriariaceae	Mediterranean to Japan, New Zealand, Chile to Mexico

A more widespread but less intense nitrogen-fixing phenomenon is that which occurs in the *rhizosphere* of certain nonlegume plants, especially tropical grasses. As discussed in Section 11.12, bacteria adapted to life in the rhizosphere are called **rhizobacteria**. Rhizobacteria that benefit plant growth and development are referred to as plant growth–promoting rhizobacteria (PGPR). Many PGPR bacteria belong in the genera *Spirillum*, *Rhizobium*, and *Azotobacter* (see Table 13.4). These microorganisms obtain their energy supply for their nitrogen-fixation from the exudates of plant roots.

Scientists have reported a wide range of rates for rhizosphere nitrogen fixation with the highest values observed in association with certain tropical grasses. Even if typical rates are only 5–30 kg N/ha/yr, the vast areas of tropical grasslands suggest that the total quantity of nitrogen fixed by rhizosphere organisms is likely very high (see Table 13.4). There may also be some potential to harness this type of nitrogen fixation for agriculture. In some cases inoculation of soil with certain GPB has stimulated sufficient nitrogen fixation under field conditions to significant increase productivity of food crops such as corn, rice, and wheat.

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Figure 13.26 *Transplanting rice seedlings into paddies containing the floating water fern,* Anabaena *(see* insets*), and its nitrogen-fixing cyanobacteria symbiont* Nostoc.
(Photos courtesy of Ray R. Weil)

13.12 NONSYMBIOTIC NITROGEN FIXATION[11]

Certain free-living microorganisms present in soils and water are able to fix nitrogen. Because these organisms are not directly associated with higher plants, the transformation is referred to as *nonsymbiotic* or *free-living.*

Fixation by Heterotrophs

Several different groups of bacteria and cyanobacteria are able to fix nitrogen nonsymbiotically. In upland mineral soils, the major fixation is brought about by species of several genera of heterotrophic aerobic bacteria, *Azotobacter* and *Azospirillum* (in temperate zones) and *Beijerinckia* (in tropical soils). Certain anaerobic bacteria of the genus *Clostridium* are also active in fixing nitrogen. Because pockets of low oxygen supply exist within aggregates even in well-drained soils (see Section 7.4), aerobic and anaerobic bacteria probably work side by side in many well-drained soils. These organisms obtain their carbon either from root exudates in the rhizosphere or by saprophytic decomposition of SOM, and they operate best where soil nitrogen is limited.

The amount of nitrogen fixed by these heterotrophs varies greatly with the pH, soil nitrogen level, and sources of organic matter available. In some natural ecosystems these organisms undoubtedly make an important contribution to the nitrogen needs of the plant community. Because of limited carbon supplies, in conventional agricultural systems they probably fix only 5–20 kg N/ha/yr (see Table 13.4); however, with proper organic matter management, it is thought that the rates may be considerably higher. If agriculturalists are able to take advantage of these organisms, the benefits would go beyond increased crop yields to include reducing the need to manufacture nitrogen fertilizer (and therefore lowering the amount of reactive nitrogen circulating in the environment) as well as reductions in N_2O emissions.

Fixation by Autotrophs

In the presence of light, certain photosynthetic bacteria and cyanobacteria are able to fix carbon dioxide and nitrogen simultaneously. The contribution of the photosynthetic bacteria is

[11]For insights into the exploitation of nonsymbiotic N fixation for agriculture, see Kennedy et al. (2004).

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uncertain, but that of cyanobacteria is thought to be of some significance, especially in wetlands (including in rice paddies). In some cases, cyanobacteria contribute a major part of the nitrogen needs of rice, but nonsymbiotic species rarely fix more than 20–30 kg N/ha/yr. Nitrogen fixation by cyanobacteria in upland soils also occurs (including in the desert microbiotic crusts discussed in Section 11.14), but at much lower levels than found under wetland conditions.

13.13 NITROGEN DEPOSITION FROM THE ATMOSPHERE

As the Earth's growing human population puts ever more reactive nitrogen into circulation, its unwanted deposition is becoming an increasingly serious global environmental problem.

Reactive nitrogen in the atmosphere consists of small, but increasing, quantities of ammonia and nitrogen oxide gases that originated as emissions from soils, oceans, vegetation, and fossil fuel combustion (especially in vehicle engines—see Section 9.6). These nitrogen gases are generally transformed into NH_4^+ or NO_3^- by reactions in clouds, and additional nitrates are formed in the atmosphere by reaction of N_2 and O_2 during lightning flashes. The term *nitrogen deposition* refers to the addition of these atmosphere-borne reactive nitrogen compounds to soils through rain, snow, dust, and gaseous absorption.

The quantity of ammonia and nitrates in precipitation varies markedly with location (see Figure 13.27). Global N deposition totals some 105 Tg N yr^{-1}. Deposition is greatest in high-rainfall areas downwind from cities (nitrate from nitrogen oxides in car exhaust and coal burning power plants), concentrated animal-feeding operations (CAFOs) (ammonium volatilized from manure), and fertilized wetland rice production. The ratio of nitrate to ammonium nitrogen deposited varies with location, the nitrate share ranging from about one-third to two-thirds.

Although the deposited nitrogen may stimulate greater plant growth in agricultural systems, the effects on forests, grasslands, and aquatic ecosystems are quite damaging. Nitrates in particular are associated with acidification of rain (as discussed in Section 9.6), but since the ammonium soon nitrifies, both forms lead to soil acidification. Nitrogen added by deposition as ammonium and nitrate from the atmosphere (or by fertilization) also impacts another soil process with important global change implications, namely, methane oxidation (Figure 13.28).

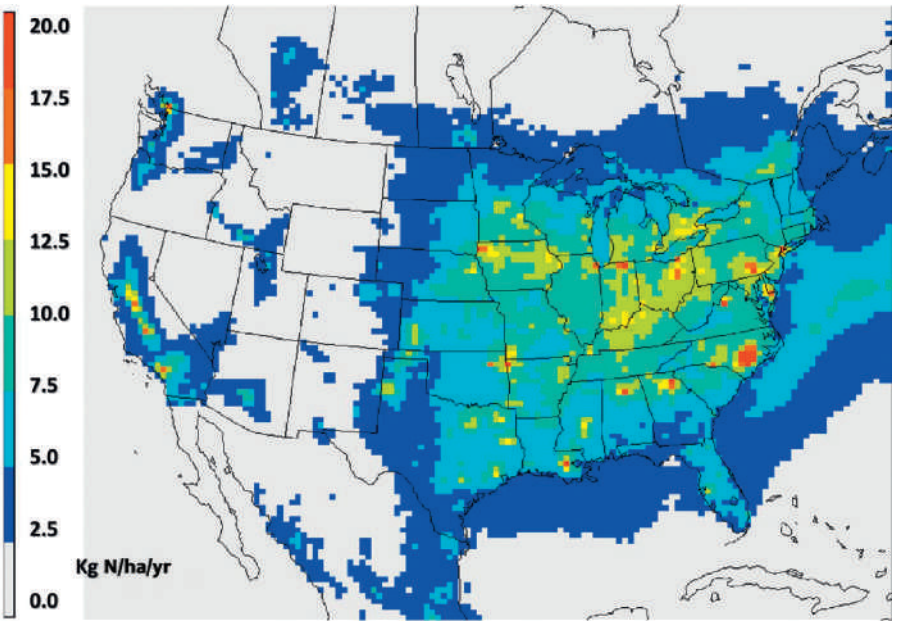

Figure 13.27 *Distribution of reactive nitrogen deposition in North America. Excessive N deposition can damage forests, estuaries, and other natural ecosystems. Highest deposition (reddest color) occurs in high-rainfall regions downwind of intensive livestock feeding, coal burning power plants, industrialized population centers, and/or rice production. Ammonia from manure and nitrogen oxides from rice paddies and fossil fuel combustion are principal sources of the N that falls with rain, snow, and dust. Although variable, there is usually more ammonium than nitrate deposited.* (From Science Advisory Board-USEPA (2011))

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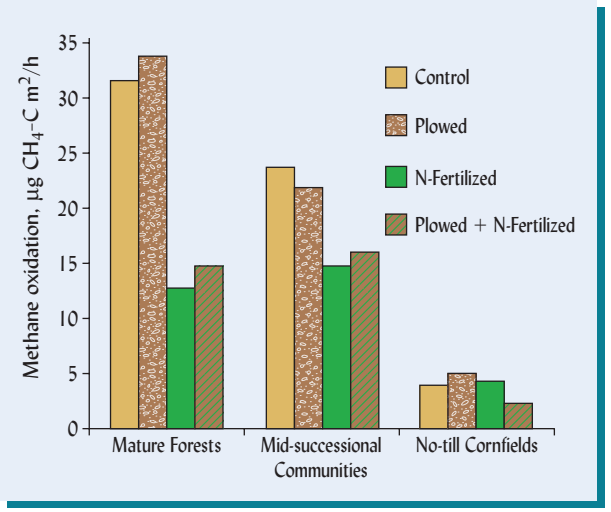

Figure 13.28 *Mineral nitrogen reduced the capacity of soils to oxidize methane and thereby remove this potent greenhouse gas from the atmosphere. Forested soils exhibited the highest rates of methane oxidization and the greatest impairment due to the addition of N. A one-time physical disturbance (plowing) had little impact. Nitrogen was applied as a solution of ammonium nitrate (100 kg N/ha). The study was on sandy loam soils (Typic Hapludalfs) in southern Michigan, USA.* [Modified from Suwanwaree and Robertson (2005)]

Methane is an important greenhouse gas affecting climate change, and its removal from the atmosphere by soil oxidation helps maintain its global balance (see also Section 12.9, Table 12.7). Forested soils have particularly high rates of methane oxidation, but also may be hardest hit by nitrogen deposition. The methane oxidation capacities of grasslands and croplands are also significantly reduced by mineral nitrogen.

Effects on Forest Ecosystems

Nitrogen in precipitation might be considered beneficial fertilizer when it falls on farmland, but it can be a serious pollutant when chronically added to some forested soils. Most forest soils are nitrogen limited—that is, they contain a surplus of carbon so that any nitrogen added is quickly tied up by microbial and chemical immobilization and very little nitrate is lost by leaching. However, a condition known as *nitrogen saturation* has been found to result from high levels of nitrogen deposition on certain mature forests in northern Europe and to a lesser extent in North America. Nitrogen saturation refers to the inability of the forest system to retain all or even most of the nitrogen received by deposition, leading to the leaching of nitrates and the associated soil acidification and loss of calcium and magnesium (as described in Sections 9.6 and 13.21). Nitrogen deposition can eventually reduce tree growth and disrupt the forest soil ecosystem in numerous ways, many of which are probably related to nitrogen saturation (Figure 13.29). Nitrogen deposition greater than about 8 kg N/ha/yr can be expected to eventually cause damage to sensitive forest and aquatic ecosystems.

The amounts of nitrogen deposited; the type of forest (e.g., deciduous or evergreen); soil properties such as texture, mineralogy, and acidity; the history of land use and age of the forest; and climatic variables all seem to influence how chronic nitrogen additions will impact forest soils and ecosystems. For example, mature coniferous forests on poorly buffered soils may reach a state of nitrogen saturation more rapidly than young, rapidly growing forests such as those subject to frequent logging or recently converted from agriculture.

Effects on Rangeland Systems

Natural rangeland ecosystems contain a wide variety of native plant species that are known for their ability to conserve nitrogen and efficiently utilize low levels of deposited nitrogen (2–5 kg N/ha/yr). However, research using deliberate nitrogen additions suggests that as nitrogen deposition increases, certain plants—often exotic species—that are highly responsive to high levels of nitrogen quickly crowd out many of the desirable native species that are adapted to grow efficiently at low nitrogen levels. Attempts that have been made to increase rangeland productivity by adding fertilizer nitrogen may increase productivity temporarily, but again, the low-nitrogen-requiring native species are soon crowded out and replaced by high-nitrogen-requiring exotic species that are generally considered weeds. The resulting systems are

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Figure 13.29 *Drastic effects of chronic high N additions on a pine forest ecosystem in Massachusetts, USA. The experimental addition of 150 kg/ha/yr (=15 g m^2/yr) of N as NH_4NO_3 since 1988 has decimated the tree canopy (a) and understory (b) compared to the unamended plot (c,d). By the 14th year of the study, 56% of the trees had died in the high N plot compared to 12% in the control plot. The high N treatment decreased soil microbial biomass by 40% and soil respiration by 35%. The fungal/bacterial ratio and microbial diversity also decreased. Much more N (inorganic and organic) was lost in leaching water from the high N plots. Foliage analyses showed significantly lower leaf calcium in the high N plots, suggesting that soil acidification and loss of calcium may have played a role in the trees' demise. The Montauk stony sandy loam soils (Typic Dystrochrepts) formed from glacial till.* (Photos courtesy of Ray R. Weil; data from Magill et al. (2004))

lower in biological diversity and productivity than the original native rangelands. This case illustrates that well-meaning efforts to increase productivity of complex, poorly understood natural ecosystems can, in fact, have the exact opposite effect.

13.14 THE NITRATE LEACHING PROBLEM

Subsurface flow of dissolved nitrogen is commonly the pathway accounting for the greatest losses of nitrogen from upland ecosystems, especially agroecosystems (Figure 13.30). Although in some cases subsurface flow carries substantial amounts of DON, the main form of nitrogen subject to leaching loss is nitrate. In contrast to positively charged ammonium ions, negatively charged nitrate ions are not adsorbed by the negatively charged colloids that dominate most soils. Therefore, nitrate ions move downward freely with drainage water and are readily leached from the soil. The loss of nitrogen in this manner is of concern for

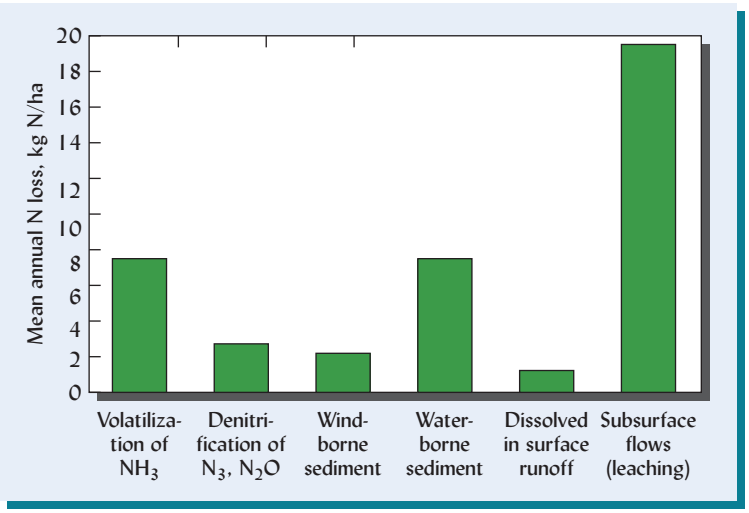

Figure 13.30 *Average annual nitrogen loss by each of six major loss pathways in the Upper Mississippi River basin.* (From USDA/NRCS (2012))

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three basic reasons: (1) the loss of this valuable nutrient is a waste that impoverishes the ecosystem (as discussed in Section 13.1), (2) leaching of nitrate anions stimulates the acidification of the soils and the co-leaching of such cations as Ca^{2+}, Mg^{2+}, and K^{+} (as described in Section 9.6), and (3) the movement of nitrate to groundwater causes several serious water-quality problems downstream. We will now examine the nature of these environmental impacts.

Water-Quality Impacts. The main water quality problem attributed to nitrogen is the leaching of nitrate to groundwater. Nitrate may reach and contaminate drinking water, causing health hazards (see Box 13.2) for people as well as livestock. The key factor for health hazards is *concentration* of nitrate in the drinking water and the level of exposure (amount of water ingested, especially over long periods). The nitrates may also eventually flow underground to surface waters, such as streams, lakes, and estuaries. The damages to surface waters are even more widespread, impairing water quality and the health of aquatic ecosystems, especially those with salty or brackish water (Box 13.3). The key factor for this kind of damage is often the *total load* (mass flux) of nitrogen delivered to the sensitive ecosystem.

BOX 13.2

SOIL, NITRATE, AND YOUR HEALTH[a]

Mismanagement of soil nitrogen can result in levels of nitrates in drinking water (usually in groundwater) and food (mainly leafy vegetables) that may seriously threaten human health. While nitrate itself is not directly toxic, once ingested, a portion of the nitrate is reduced by bacterial enzymes to nitrite, which is considered toxic.

The most widely known (though actually quite rare) malady caused by nitrite is **methemoglobinemia**, in which the nitrites decrease the ability of hemoglobin in the blood to carry oxygen to the body cells. Since inadequately oxygenated blood is blue rather than red, people with this condition take on a bluish skin color. This symptom, and the fact that infants under three months of age are much more susceptible to this illness than older individuals, accounts for the condition being commonly referred to as "blue baby syndrome." Most known deaths from this disease have been caused by infant formula made with high-nitrate water. With the aim of protecting infants from methemoglobinemia, governments have set standards to limit the nitrate concentrations allowed in drinking water (Figure 13.31). In the European Union it is 50 mg/L nitrate (= 11 mg/L nitrate-N) and in the United States this limit is 10 mg/L nitrate-N (= 45 mg/L nitrate).

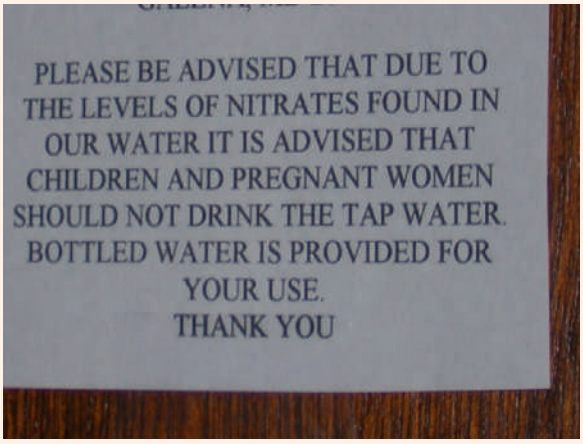

Figure 13.31 *Warning on hotel room door in heavily agricultural watershed.* (Photo courtesy of Ray R. Weil)

Of greater potential concern is the tendency of nitrate to form N-nitroso compounds in the stomach by binding with such organic precursors as amines derived from proteins. Certain N-nitroso compounds are known to be highly toxic, causing cancer in some 40 species of test animals, so the threat to humans must be given serious consideration. Nitrates (or nitrites formed therefrom) have also been reported to promote certain types of diabetes, stomach cancers, interference with iodine uptake by the thyroid gland, and certain birth defects. While documenting cause and effect in chronic diseases is always uncertain, many of these effects appear to be associated with nitrate concentrations much lower than the drinking water limits just mentioned.

On the other hand, several research studies suggest that ingestion of nitrate does no harm and may actually provide protection against bacterial infections and some forms of cardiovascular diseases and stomach cancers. Therefore, while a precautionary approach is probably wise, we must conclude that the "jury is still out" on the health risks of nitrates in drinking water and vegetables.

[a]For reviews of nitrate effects on health, see Santamaria (2006) and L'hirondel and L'hirondel (2002). For a contrary view, see Addiscott (2006).

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BOX 13.3

NITROGEN POLLUTION: DEAD ZONE IN THE GULF OF MEXICO

Under natural conditions, low levels of nitrogen limit aquatic algae growth—especially in estuaries where salty or brackish water inhibits N-fixing algae. Increased human input of nitrogen can remove this constraint, causing choking and sometimes toxic growth of aquatic plants and algae. The resulting degradation of aquatic ecosystems is undoubtedly the most widespread water-quality problem induced by nitrogen pollution. Worldwide, more than 400 estuaries have suffered severe declines in water quality and biodiversity. Major examples include the Yangtze River and Pearl River estuaries on the coast of China, the lower Chesapeake Bay on the Atlantic Coast of the United States, and the Mississippi River estuary in the Gulf of Mexico.

In the Gulf of Mexico off the coast of Louisiana, USA, an enormous "dead zone" of water some 4–60 m deep reaches from the mouth of the Mississippi River westward nearly 500 km to Texas, USA. Nutrient-rich freshwater carried by the river glides over the cooler, saltier (and therefore heavier) Gulf water. The nutrients (mainly N, but also P and Si) stimulate explosive growth of algae, which sink to the bottom when they die (Figure 13.32). While decomposing this dead tissue, microorganisms deplete the oxygen dissolved in the water to levels unable to sustain animal life. Fish, shrimp, and other aquatic species either migrate out of the zone or die. This state of low oxygen in the water (less than 2–3 mg O_2/L) is known as **hypoxia**, and the process that brings it about is called **eutrophication** (see also Box 14.1 for eutrophication caused by phosphorus mainly in fresh waters).

Concentrations of N in the Mississippi river have tripled in the past 30 years, mainly due to human activities, especially those in agriculture. Critical assessments suggest that only about 10% of the N delivered by the river comes from sewage treatment plants and other point sources; some 75% comes from farmland runoff carrying N from fertilizers, soil, and manure. Major efforts are required to help farmers and others improve their N use efficiency and reduce the transformation of this valuable nutrient into a pollutant.

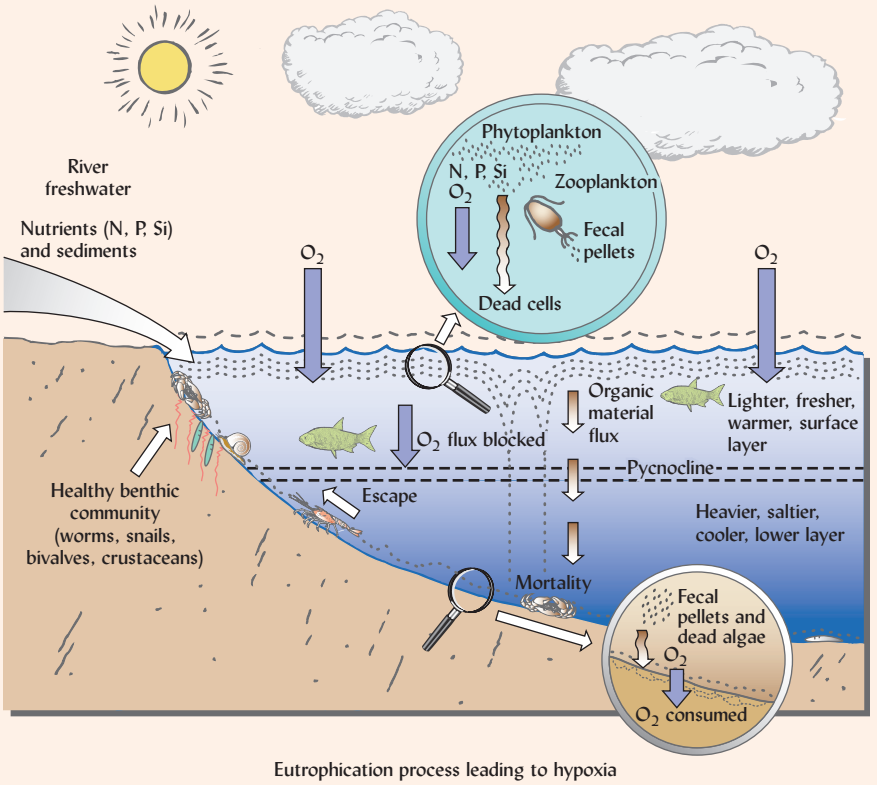

Figure 13.32 *Eutrophication process leading to hypoxia. From CAST (1999). For a detailed account of the causes and effects of the Gulf of Mexico dead zone, see Boesch et al. (2009).*

The total nitrogen load may be comprised partly of organic and ammonium forms of N transferred from the land in surface runoff or on eroded soil material, but N leached through the soil profile as nitrate (along with soluble organic N) is often the main contributor. The quantity of nitrate lost in drainage water depends on two factors: (1) the volume of water leaching through the soil and (2) the concentration of nitrates in that drainage water.

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Volume of Leaching Water. The volume of leaching water is influenced by rates of precipitation, irrigation, and evapotranspiration (Section 6.1), as well as by soil texture and structure. Sandy soils in humid regions are therefore highly susceptible to leaching. By contrast, unirrigated soils in arid regions are expected to undergo very little leaching (yet over 1000s of years, occasional rains may leach substantial amounts of nitrate deep into desert soils!). Conservation tillage increases water infiltration at the expense of surface runoff, thereby also increasing the volume of water available for leaching. Growth of perennial vegetation or use of cover crops can decrease leaching by removing both nitrogen (by uptake) and water (by transpiration).

Concentration of Nitrogen. The concentration of nitrate in the leaching water is largely dependent on the size of the soil nitrate pool during periods of leaching. The nitrate present, in turn, reflects the balance between removal of nitrogen from this pool by plant uptake or immobilization and the input of nitrogen into the nitrate pool by mineralization, fertilization, and atmospheric deposition. For example, pristine mature forests usually maintain a very close balance between nitrogen taken up by trees and nitrogen returned as litter. Leaching water contains only about 0.1 mg nitrate-N/L, and only 1 or 2 kg of N/ha is lost annually to groundwater. However, deposition from the atmosphere can increase inputs to the nitrate pool, while disturbances such as timber harvest can reduce plant uptake out of the pool, leading to leachate concentrations of 2–3 mg nitrate-N/L and annual leaching losses greater than 25 kg N/ha.

Groundwater and streams draining watersheds with intense agricultural land use are commonly much higher in nitrate than those draining forested watersheds. Heavy nitrogen fertilization of crops (especially vegetables and some grain crops) can be a major source of excessive nitrate because the crops rarely absorb more than half of the nitrogen applied. Watersheds with many CAFOs are often the most polluted with nitrate because of the enormous quantities of nitrogen-rich animal manure produced (see Sections 13.15 and 16.4).

Timing of Nitrogen Input. In humid-temperate (Udic) and Mediterranean (Xeric) climates, the potential for nitrate leaching is lowest in midsummer when plants are using large amounts of both water and N. Leaching water volumes and nitrate levels are commonly highest in early spring and late fall and winter (if soils are not frozen) when plants are not intensively using water or N, leaving both available to leach. The synchrony between the production of nitrate by mineralization and the uptake of N by plants is greatest where perennial vegetation is grown and poorest where annual crops leave the soil bare in early spring and late fall.

Application of the entire amount at the beginning of the season may result in much of the nitrogen leaching below the root zone before annual plants have had a chance to use it (as in the high N-rate example in Figure 13.33). This is especially true where soils are sandy or where precipitation (rainfall and irrigation) is high early in the season. Under these conditions, it is advisable to delay N application until plants have established an extensive root system and are about to enter their phase of rapid growth and high N uptake rate. The amount of nitrogen to *side dress* at this time may be determined by: (1) measuring the nitrate accumulated so far in the soil (a pre-sidedress nitrate soil test, PSNT) or (2) feeding site-specific soil, weather and management data into a sophisticated computer program that models the gains and losses of nitrogen in the soil up to that point in the season (e.g., Adapt-N, http://adapt-n.cals.cornell.edu/). At the end of the season, a cornstalk nitrate test (CSNT) can be used to assess whether too much or too little nitrogen was applied that year. Widespread experience shows that such improved management allows the application of less nitrogen while increasing economic returns, maintaining crop yields, reducing the level of N susceptible to leaching loss after crop harvest.

An even more conservative alternative is to split the total N application for the growing season into several small doses. For example, **split application** for an annual crop might involve applying a small portion (10–20%) of the N at planting time, and providing most of the N in a second—and possibly third—application latter in the season when the plants are larger and their rate of N uptake is high. Although split or delayed application of fertilizer may require some extra effort and special machinery, it often is justified by improved N use efficiency, increased yields, and greater profitability.

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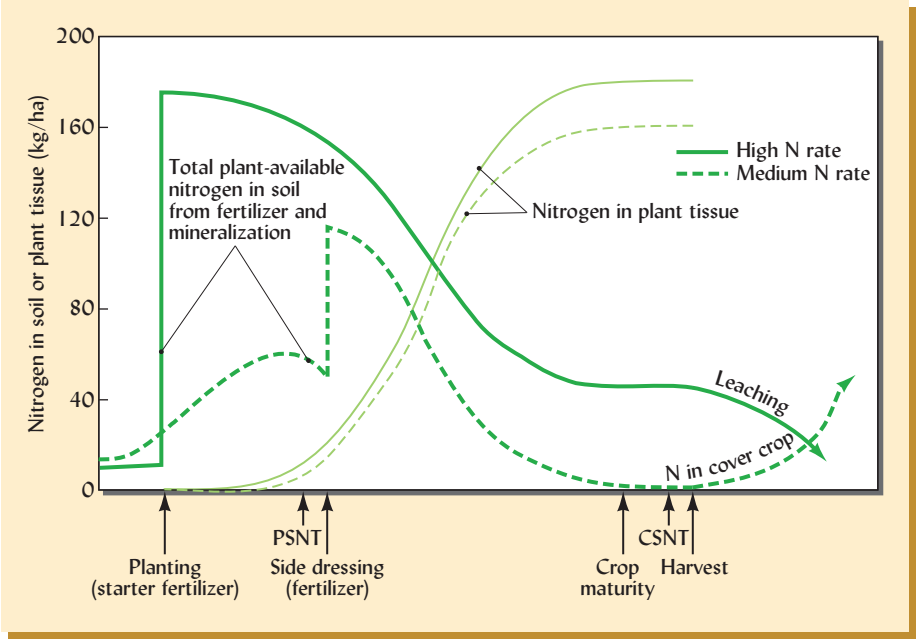

Figure 13.33 *Two nitrogen management systems for corn production. One system that has been popular in the U.S. Corn Belt (solid lines) involves very high nitrogen applications and continuous corn culture. At least 150–180 kg N/ha is applied as fertilizer at planting time. Some of this N is leached into the subsoil before rapid crop N uptake begins. Later, when the crop matures and is harvested, much soluble nitrogen remains in the soil, probably in the form of nitrates. If not captured by a cover crop planted in the corn at harvesttime, the excess nitrogen is subject to leaching during the fall and winter months. This leads to contamination of groundwater and, eventually, surface water. More environmentally sound systems involve crop rotations that include legumes, or if corn is grown continuously, the rate of nitrogen fertilizer is greatly reduced (broken lines). Little if any N fertilizer is applied at planting time; rather it is applied as a side dressing just before the most rapid growth stage. In the alternative medium N rate scenario, crop yields and economic returns are about the same, but the N remaining in the soil at crop harvest is low, a cover crop captures and recycles deeper nitrate and groundwater contamination is minimized.* (Diagram courtesy of Ray R. Weil)

Management to Reduce Losses. Even in regions of high leaching potential, careful soil management can prevent excessive nitrate losses. Applications of fertilizer and manure should be modest in amount and timed to provide nitrogen when actively growing plants are able to absorb it. Nitrogen-scavenging winter cover crops (Section 16.2) should be planted immediately following summer annual crop harvest to take up the unused nitrates before they can leach away (see Figure 13.33). If such guidelines are followed, nitrogen leaching may be kept to less than 5–10% of the nitrogen applied.

Reversing Nitrate Leaching in the Humid Tropics. Much of the nitrate mineralized in certain highly weathered, tropical Oxisols and Ultisols leaches below the root zone before annual crops such as corn can take it up. Soil scientists in Africa have discovered that some of this leached nitrate is not lost to groundwater. Instead, the highly weathered and acid clays deep in the subsoil adsorb the nitrate on their anion exchange sites (see Section 8.11). Deep-rooted woody perennials such as *Sesbania* trees or pigeon peas are capable of taking up this subsoil nitrate. If grown in association with annual food crops, the perennials subsequently enrich the surface soil when they shed their leaves, making this pool of once-leached nitrogen available again for food production (Figure 13.34). Such **agroforestry** practices have the potential to improve both crop production and environmental quality in the humid tropics (see also Section 20.10).

13.15 PRACTICAL MANAGEMENT OF SOIL NITROGEN

Sustainable nitrogen management aims to achieve three goals: (1) the maintenance of SOM to ensure adequate long-term nitrogen supplies in the soil, (2) the regulation of the soluble forms of nitrogen to ensure that plant needs are met, and (3) the minimization of environmentally damaging losses of nitrogen from the soil–plant system, including nitrate and soluble organic nitrogen in leaching and runoff water, as well as ammonia and nitrogen oxides in gaseous emissions.

A particular type of soil in any given combination of climate and farming system tends to assume what may be called a *normal* or *equilibrium content* of nitrogen. Consequently, under ordinary methods of cropping and manuring, any attempt to permanently raise the nitrogen content to a level higher than this will result in unnecessary waste as nitrogen

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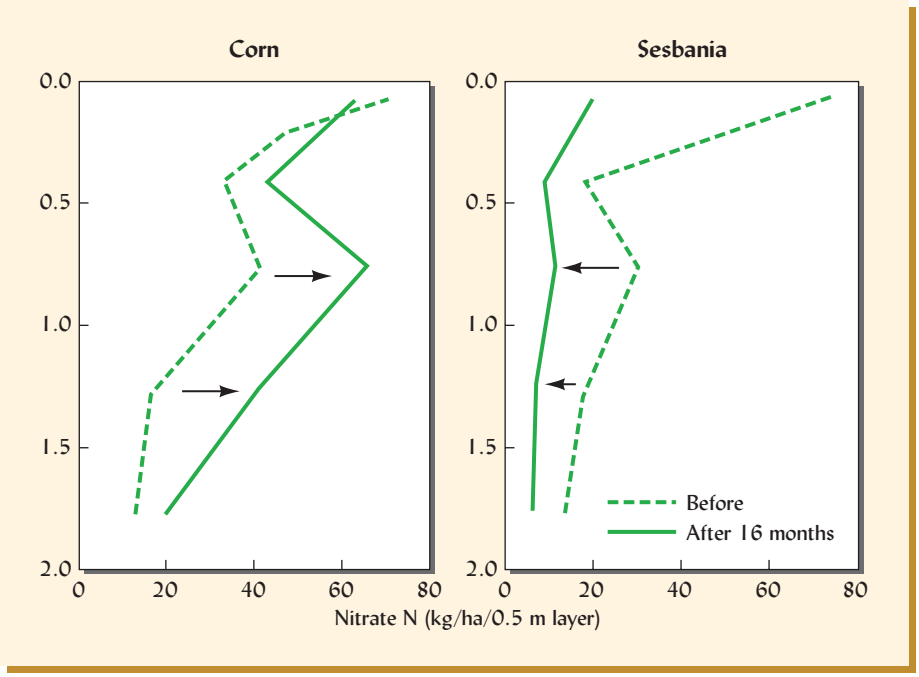

Figure 13.34 *Depth distribution of nitrates in an Oxisol in western Kenya before planting either corn or a fast-growing tree,* Sesbania, *and after growing three crops of fertilized corn (in 16 months) and continuous* Sesbania. *Note that the* Sesbania *markedly decreased soil nitrates to a depth of about 2 m. Separate root studies (Mekonnen et al., 1997) showed that 31% of the* Sesbania *roots were located between 2.5 and 4 m in depth. Compare to Figure 13.54.* [From Sanchez et al. (1997)]

leaches, volatilizes, or is otherwise lost before it may be used. The equilibrium level of soil nitrogen is governed by the management practices employed and is likely to change as they are changed. For example, if cultivated soil that is initially low in organic matter and nitrogen is planted to perennial grass and fertilized or mixed with legumes, the cessation of tillage and high rate of root matter return will cause SOM to build up quickly (see Section 12.8). If this long-term grassland is then plowed under, the reverse will take place, and the nitrogen stored over the years will be rapidly released—possibly causing a flush of nitrate leaching.

Using Nitrogen Fertilizers Wisely

Ammonium and nitrate ions from fertilizer are taken up by plants and participate in the nitrogen cycle in exactly the same way as ammonium and nitrate derived from organic matter mineralization or other sources. In fact, most of the N added as soluble fertilizers enters the biological cycle *before* the fertilized plants use it (see Figure 13.35). Nonetheless, the application of soluble fertilizers results in greater concentrations of these nitrogen ions than would be found in unfertilized soils. Plants and microorganisms may not be able to assimilate the applied nitrogen fast enough to prevent major losses by leaching, surface runoff, denitrification, and ammonia volatilization. Box 13.4 describes some technologies that can make nitrogen fertilizers less prone to these environmentally damaging losses. However, even with the best fertilizer technologies, it is still important to avoid applying more nitrogen than is actually needed.

Fertilizer nitrogen should be considered only as a *supplement* to the nitrogen made available from nitrogen deposition from the atmosphere, mineralization from SOM, fixation by legumes, and release from current or past applications of animal manure or other organic materials. That is, the amount of N applied as fertilizers should be reduced in accordance with contributions from these sources to the pool of plant-available nitrogen. This strategy is often referred to as "taking nitrogen credits" for these nonfertilizer sources.

Preventing N Losses

Nitrogen losses by leaching and denitrification from agricultural land generally become problematic only when nitrogen fertilization exceeds the amount needed to fill the gap between crop uptake needs and the supply from the other sources just mentioned. The need for

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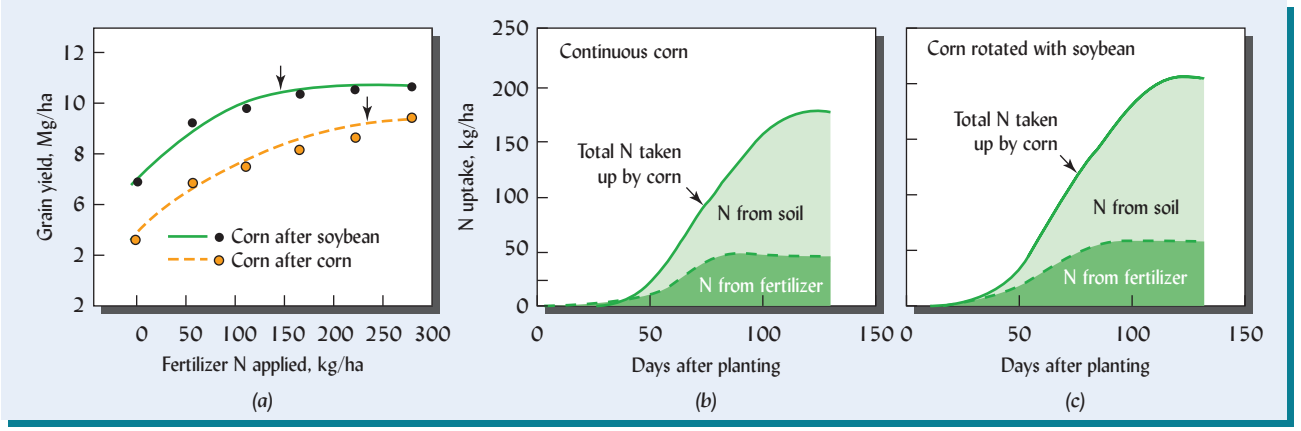

Figure 13.35 *Crop rotation can increase yields and reduce fertilizer requirements. (a) The amount of fertilizer nitrogen required (↓) for optimal corn yields was about 150 kg N/ha in the corn–soybean rotation (green line), but over 250 kg N/ha in the continuous corn system (gold line). These Flanagan silt loam (Aquic Argiudoll) soils supported either corn every year or corn every second year alternating with soybeans for five corn crops. (b) The use of isotopically labeled fertilizer ($^{15}NH_4NO_3$) in another study showed that even when a relatively high rate was applied (168 kg N/ha), most of the corn's N needs did not come directly from the fertilizer but from the mineralization of soil organic matter. This was especially true in the latter part of the growing season. By harvest time, the fertilizer-derived nitrogen taken up by the corn represented less than one-third of the nitrogen taken up by the plants and accounted for less than one-third of the fertilizer nitrogen applied to the soil. (c) Corn grown in rotation with soybeans took up more nitrogen from both soil and fertilizer sources than did corn grown after corn. These data are averages for two years and two soils (a silt loam Ustoll and a loam Udoll) in Kansas, USA, but the results are typical of those found in many parts of the world (compare to Table 16.15). The rotation corn maintained some yield advantage even when high amounts of nitrogen were applied, indicating that in addition to increased nitrogen availability after soybeans, the crop rotation conferred other benefits, such as pest reduction or improved soil microbial activity. Crop rotations involving more than two crops usually produce even greater benefits, especially if they include cover crops, perennial grass-legume hay or pasture.* [Data in (a) from Gentry et al. (2013) and in (b,c) from Omay et al. (1998)]

commercial nitrogen fertilizer will be governed by the degree to which the manager is able to integrate symbiotic nitrogen fixation, manure and residue recycling, and loss minimization practices into the farming system. Not every system needs to export a nitrogen-containing product. In the case of lawn grass, the aim of management is to produce a healthy lawn, not grass clippings for harvest. In contrast to the heavy fertilization used on many lawns, the nitrogen-balance principles just discussed suggest that if the clippings are not removed after every mowing, then little or no nitrogen will be removed and little fertilizer need to be applied (see Figure 13.39).

Legume Cover Crops Reduce the Need for Nitrogen Fertilizer

A legume cover crop system may be able to replace part or all of the nitrogen fertilizer normally used to grow an annual cash crop (Figure 13.40). The cover crop is usually killed mechanically or by herbicide spray before the main crop is planted. The cover crop residues can be left on the surface as a mulch in a no-till system (see Section 17.6) or plowed under in a conventional tillage system. When evaluating the feasibility of using cover crops, consideration should be given to the many other benefits of cover crops in addition to nitrogen supply (Section 16.2) as well as the costs and risks of growing the cover crop.

As cover crop residues decay, nitrogen is supplied to the following main crop over a period of several months, rather than all at once as with a soluble fertilizer application. In most cases low C/N ratio legume residues decay rapidly enough to keep up with crop nitrogen demands (see Section 12.3). Legume cover crop systems have been adapted for vineyards, rice paddies, grain crops, vegetable fields, and home gardens wherever there is sufficient water to support both the cover crop and the main (summer) crop. Cover crops are increasingly important in organic farming systems because environmental restrictions on excessive phosphorus application (Sections 16.2 and 16.12) are forcing organic farmers to reduce their traditional

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BOX 13.4

CONTROLLING NITROGEN LOSSES WITH FERTILIZER TECHNOLOGY

A major challenge in managing nitrogen (N) fertilizers is to supply plant-available N at the proper time, in sufficient but not excessive amounts, and with a minimum of loss to the environment. Here we will discuss three types of fertilizer technology that can help meet this goal (Figure 13.36).

1. **Slow-release fertilizers.** Most synthetic nitrogen fertilizers contain readily water soluble N, but the N in *slow-release fertilizers* is formulated to dissolve in moist soil slowly over a period of weeks or months. In this way, ammonium and nitrate concentrations may be better synchronized with plant N uptake requirements, thus avoiding excessive N losses. Figure 13.37 illustrates dramatic reductions in nitrate leaching under turfgrass that can be achieved by replacing water-soluble fertilizers with organic or slow-release materials. Slow release of N may be achieved by the mineralization of compost (see Section 12.10), digested sewage sludge (e.g., Milorganite®) or other stabilized organic materials. However, most slow-release N fertilizers are made by treating highly soluble urea fertilizer with materials that slow its dissolution or inhibit its hydrolysis to ammonium (Figure 13.36). Urea–formaldehyde, isobutylidene diurea (IBDU), resin-coated fertilizers (e.g., Osmocote®), polymer and sulfur-coated urea are all examples of slow-release N fertilizers. In the case of the latter, the sulfur content (10–20%) itself may be beneficial where sulfur is in low supply (Section 13.18) or problematic where the extra acidity generated by the sulfur (Section 13.22) would be undesirable. Sulfur-coated urea should not be used in flooded rice paddies as reduced iron will combine with the sulfur to form insoluble FeS, locking up the N in the fertilizer. Excellent controlled release characteristics have recently been achieved with polymer coatings that do not react with iron in anaerobic soils. Figure 13.38 describes dramatic reductions in emissions of ammonia and nitrous oxide gases using plastic polymer coatings to make fertilizer granules release urea slowly during an entire rice growing season instead of dissolving immediately upon application to flooded paddy soils. Slow-release fertilizers cost from 1.5 (for sulfur-coated urea) to 5 times as much as plain urea per unit of N. Therefore, they are most widely used for high-value plant production (e.g., certain vegetables, turfgrass, and ornamentals) where the cost of fertilizers is not critical. Their use on turfgrass is popular because they are not likely to cause fertilizer burn and because they provide the convenience of fewer applications.
2. **Urease inhibitors.** The enzyme urease is ubiquitous in soils and on surface residues. When urea is applied in the field, urease rapidly catalyzes the hydrolysis of urea to form ammonium carbonate which in turn releases ammonium ions into the soil solution. If the urea is applied to the soil surface, and especially if the soil pH is above 7.0, the ammonium ions (NH_4^+) will readily convert to ammonia gas (NH_3) and volatilize from the soil. Urease inhibitors, such as N-(n-butyl) thiophosphoric triamide (NBPT), added to urea fertilizer can conserve N if conditions favor NH_3 loss. Yield increases that repay the added cost of NBPT fertilizer have been observed in about 1/3 of such cases.
3. **Nitrification inhibitors**[a] are compounds that inhibit the activity of the *Nitrosomonas* bacteria, which convert NH_4^+ to NO_2^- in the first step of nitrification. (Note from Eq. (13.5) that a chemical inhibiting *Nitrobacter* would *not* be useful, as this would cause toxic nitrite (NO_2^-) to accumulate.) As long as N remains as NH_4^+ it has little susceptibility to loss by leaching and does not transform into the greenhouse-forcing gases (N_2O and NO) by denitrification. Therefore, N fertilizers might be used more efficiently if the conversion of NH_4^+ to NO_3^- could be slowed down until the crop is ready to make use of the mobile NO_3^-. To this end chemical companies have developed such nitrification inhibitors as dicyandiamide (DCD), nitrapyrin (N-Serve®), 3, 4-Dimethylpyrazole phosphate (DMPP), Ca-carbide and etridiazol (Dwell®). When mixed with nitrogen fertilizers, these compounds can temporarily prevent NO_3^- formation. The key word here is *temporarily*, for when conditions are favorable for nitrification, the inhibition usually lasts only a few weeks (less if soil temperatures are above 20 °C). Fertilizers treated

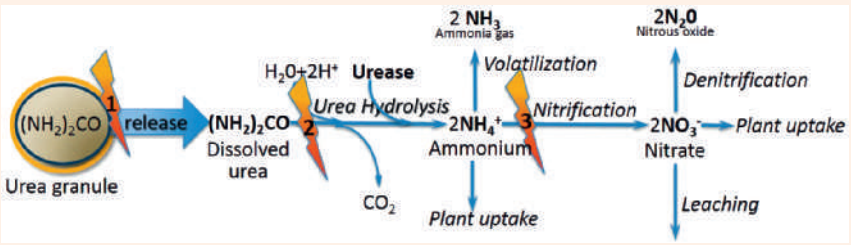

Figure 13.36 *Three types of inhibitors (jagged blades) designed to make fertilizer nitrogen less prone to loss: (1) Coatings that inhibit slow the release of urea from fertilizer granules; (2) chemicals that inhibit the urease enzyme thus slowing hydrolysis of urea to ammonium thus limiting formation of ammonia gas and nitrates; and (3) nitrification inhibitors that slow nitrate formation from ammonium, thus reducing losses by leaching and denitrification.* (Diagram courtesy of Ray R. Weil)

(continued)

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BOX 13.4

CONTROLLING NITROGEN LOSSES WITH FERTILIZER TECHNOLOGY *(CONTINUED)*

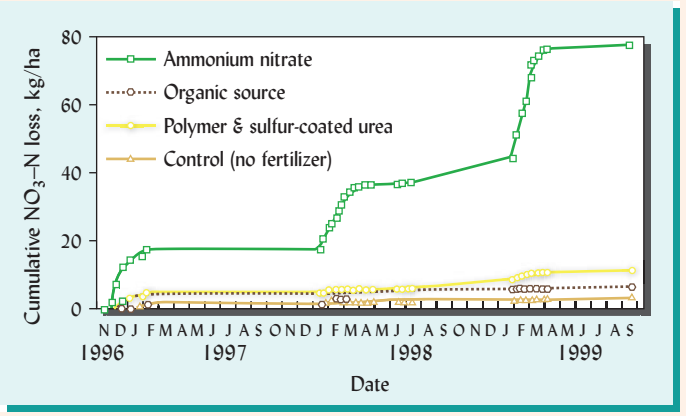

Figure 13.37 *Nitrate leaching from cool season turfgrass fertilized with 50 kg N/ha in November, May, and July of each year in the form of (1) ammonium nitrate, 100% soluble N, (2) polymer and sulfur-coated urea with dissolution rate of 25%/week, or (3) a composted turkey litter organic source with 5% total N. The control was unfertilized. The Paxton fine sandy loam soil (Oxyaquic Dystrudepts) was not irrigated, and leaching occurred mainly between November and March each year when the grass was dormant. Funnels (gravity lysimeters) embedded 38 cm under the natural soil profile were used to collect the leachate.* (From Guillard and Kopp (2004), with permission from ASA-CSSA-SSSA)

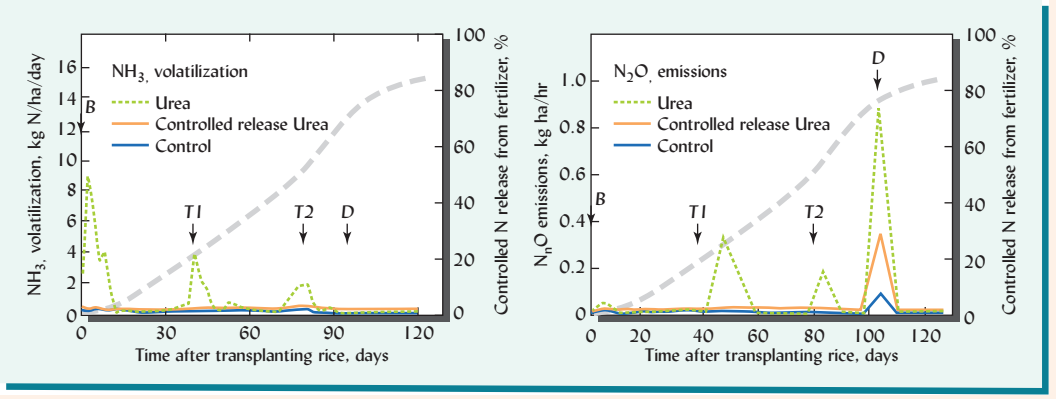

Figure 13.38 *An example of fertilizer technology that could potentially reduce unwanted N losses to the atmosphere from fertilized rice paddies. The normal best management practice is to apply N as urea fertilizer in three doses (vertical arrows): a basal dose (B) when the rice seedlings are first transplanted, a second (T1) and third (T2) dose 40 and 80 days after transplanting. The dotted green line shows the N loss as ammonia volatilization* (left panel) *and N_2O emissions* (right panel) *when conventional urea fertilizer granules were used to apply a total of 200 kg N/ha. Note the burst of emissions after each dose was applied. A special thermoplastic resin coating was developed to control the dissolution of urea fertilizer granules such that N is released gradually (thick dashed gray line) in synchrony with N uptake by rice plants from seeding through transplanting to crop maturity. Although the full 200 kg N/ha was applied all at once at transplanting, the use of this controlled release fertilizer prevented nearly all loss of N to the atmosphere (orange lines) by avoiding the presence of a large excess of soluble N. However, when the flooded rice fields were drained (arrow labeled D) toward the end of the growing season, the partial aeration of the soil did result in a burst of N_2O emissions from all treatments, even the unfertilized control (blue line).* (Redrawn from Yang et al. (2013))

with these chemicals are expensive and typically pay for themselves by saving N only in rainy conditions on sandy soils (by reduced leaching) and on temporarily waterlogged soils (by reduced denitrification).

Biological inhibition of nitrification may offer a new way of controlling nitrate formation without the limitations and expense of synthetic fertilizer additives. Researchers have discovered that root exudates produced by a tropical forage grass (*Brachiaria humidicola*) effectively inhibit *Nitrosomonas*, accounting for the high efficiency of N use in certain pasture systems. Scientists hope to transfer the nitrification inhibition gene from *B. humidicola* to other plants, with the aim of achieving widespread improvements in N use efficiency and reductions in N impacts on groundwater and greenhouse gases.

[a]For a meta-analysis of research on nitrification inhibitors and their potential benefits, see Qiao et al. (2015). For information on biological nitrification inhibition in tropical pastures, see Ishikawa et al. (2003).

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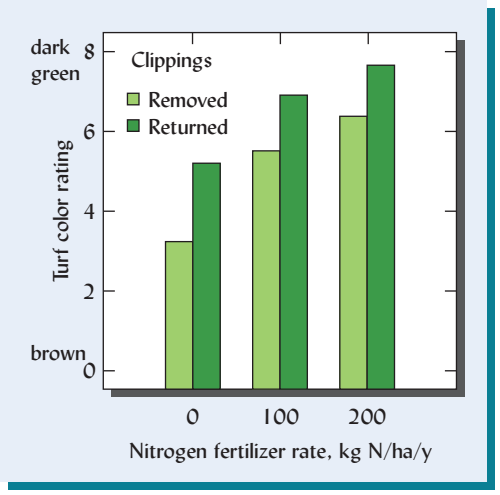

Figure 13.39 *Turfgrass quality as influenced by nitrogen fertilizer and return or removal of grass clippings. Note that the practice of leaving the grass clippings on the lawn to recycle the nitrogen seemed to provide as much benefit as 100 kg/ha of fertilizer N, providing acceptable quality turf even with no N application. Modern rotary mowers cut grass leaves into tiny pieces that easily sift down between the grass blades and decompose rapidly without accumulating as undesirable thatch. If substituted for some or all N fertilizer, recycling of clippings can reduce the significant contribution that lawns make to N in runoff in urban and suburban watersheds.* [Drawn from data in Heckman et al. (2000)]

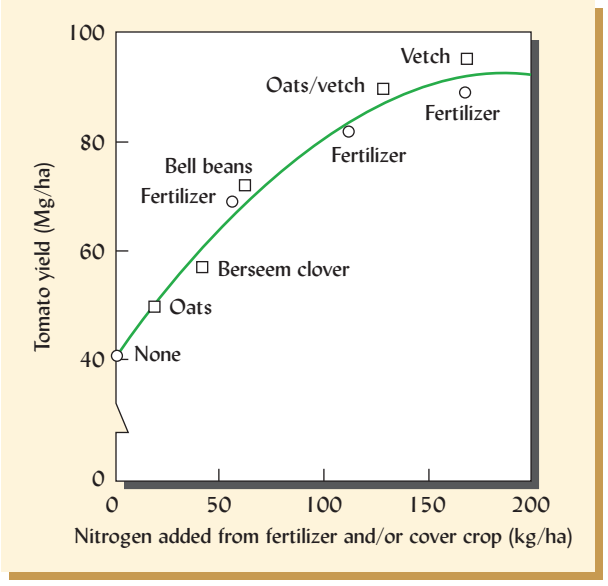

Figure 13.40 *Effects of winter cover crops and inorganic fertilizer on the yield of the following main crop of processing tomatoes grown on a Xeralf soil in California, USA. The amount of nitrogen shown on the x-axis was added either as inorganic fertilizer or as aboveground residues of various cover crops. Note that nitrogen from either source seemed to be equally effective. For the tomato crop, which requires nitrogen over a long period of time, vetch alone or vetch mixed with oats produced enough nitrogen for near-optimal yields.* [Data abstracted from Stivers et al. (1993). © Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida]

dependence on purchased manure and compost for nitrogen (which contain high levels of phosphorus).

In temperate regions, winter annual legumes, such as vetch, clovers, and peas, can be sown in fall after the main crop harvest or, if the growing season is short, they can be seeded by airplane or helicopter while the main crop is still in the field. After surviving the coldest part of the winter in a dormant state, the cover crop will resume growth in spring and associated microorganisms will fix as much as 3 kg/ha of nitrogen daily during the warmer spring weather. The amount of nitrogen provided is therefore partially determined by how long the cover crop is allowed to grow.

Legume Main Crops in Rotations

A detailed consideration of different cropping sequences (**crop rotations**) is beyond the scope of this book, but the nutrient-management aspects of rotating legumes with nonlegumes deserve mention here. A legume main crop grown one year may substantially reduce the amount of nitrogen fertilizer that needs to be used to grow a subsequent nonleguminous crop the next year. However, unlike for the legume cover crops just discussed, most of the biomass and accumulated nitrogen in the legume main crop is removed with the crop harvest. Perennial forage legumes like alfalfa tend to supply the greatest amounts of nitrogen because of their large root contribution, but the nitrogen contributions of grain legumes (e.g., soybeans or peanuts)

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should also be taken into account when planning fertilizer applications to nonlegumes that follow in the rotation. For example, many studies have shown that compared to corn grown after corn, corn grown after soybeans responds less dramatically to nitrogen fertilizer and requires less of it for optimal growth (Figure 13.35*a*).

Growing the same crop year after year on the same land generally produces lower yields of that crop and engenders more negative impacts on the soil and environment than if that crop is grown in rotation with other crops. This is true even when legumes are not part of the rotation, so more than nitrogen fixation must be involved. The improved plant productivity may result from interruption of weed, disease, and insect pest cycles; from complementary soil exploitation by differing root systems; different types of residues and nutrient requirements; synergistic effects (see Section 11.14); and, possibly, positive effects on mycorrhizal diversity (see Section 11.9). These and other phenomena may explain why, even where pests and nutrient supply are optimally controlled, crops consistently yield 10–20% more in rotations than in continuous culture.

Bringing Nitrogen Inputs into Balance with Outputs

To effectively manage nitrogen or any other nutrient, it is important to consider the balance between inputs and outputs for the system in question. The features that make a system dominated by agriculture different from a natural ecosystem are mainly: (1) the import of nitrogen in fertilizer and feed and (2) the removal of nitrogen in the harvested product. If the total N input is greater than nitrogen output contained in harvested agricultural products, the land is considered to be subject to a nitrogen excess. A small amount of such nitrogen excess may initially remain on the land as accumulated soil organic N or in plant biomass, but eventually the excess nitrogen will take the form of environmentally (and financially) damaging losses from the system. The map in Figure 13.41 shows "hot spots" of excess nitrogen in China, Northern India, central USA, and Western Europe. Perhaps one third of the global nitrogen surplus is

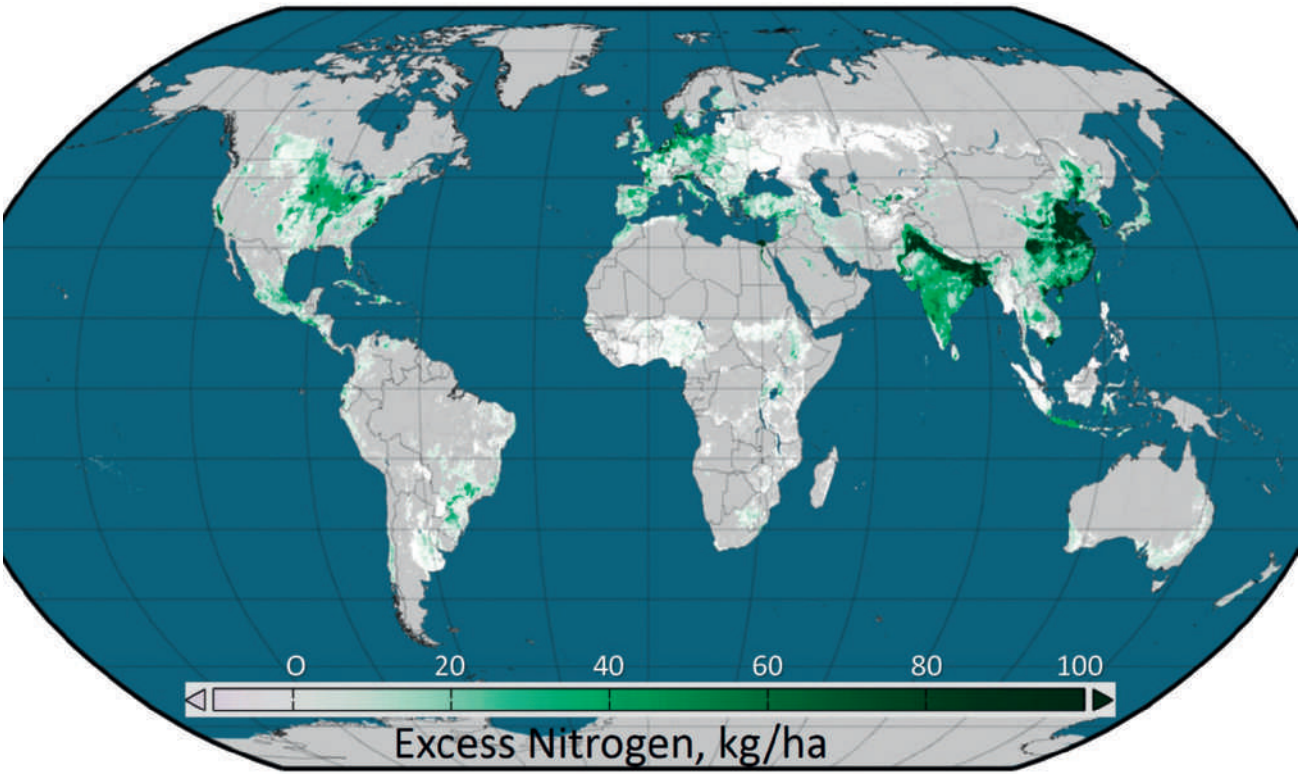

Figure 13.41 *Global distribution of excess nitrogen application to agricultural land producing the major cereals such a maize, wheat and rice. The darker the green color, the greater the imbalance between nitrogen inputs and crop removals, resulting in environmental losses of the excess. White areas are not cereals cropland. The excessive use of nitrogen in north India, east China, a few parts of the USA, and northern Europe are highlighted.* [Modified from materials in Mueller et al. (2014)]

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concentrated on just 10% of the world's croplands. The lost excess nitrogen ends up causing environmental damage via air (e.g., N_2O, NH_3 gases), water (e.g., NO_3^- and dissolved organic N), or soil (nitrogen saturation and acidification). In many agricultural areas devoted to intensive crop production, the excess nitrogen is mainly due to applications of fertilizer beyond what the crops can actually use (see Section 16.13). In other areas, where there are CAFOs (concentrated animal-feeding operations), the imbalance stems from the fact that much nitrogen is imported in the feed because the system for raising of animals is not well integrated on the land with the production of their feed (see Section 16.4). The data in Table 13.6 quantify changes, experienced, and expected, in the balance between various nitrogen inputs and outputs for the world's agricultural land. The data specific to China in Table 13.6 illustrate the magnitude of nitrogen excess in a country that imports a significant proportion of the livestock feed for its many CAFOs. Note that for the country of China as a whole, the manure and atmospheric deposition nitrogen inputs to agricultural land were sufficient to meet the nitrogen taken off the land as harvested agricultural products.

The principles discussed in this chapter suggest several basic strategies for achieving a rational reduction of excessive nitrogen inputs while maintaining or improving production levels and profitability in agricultural enterprises. These approaches include: (1) taking into account the nitrogen contribution from *all* sources and reducing the amount of fertilizer applied accordingly; (2) improving the efficiency with which fertilizer and organic amendments (e.g., manure) are used; (3) avoiding overly optimistic yield goals that lead to fertilizer

Table 13.6
INPUTS AND OUTPUTS OF NITROGEN FOR AGRICULTURAL LAND AT DIFFERENT TIMES[a]
Actual data are shown for estimates of global amounts of N for world agricultural land in the years 1970 and 2000 and for per hectare amounts of N in Chinese agricultural land in 2008. Projected data for the year 2050 is also shown as modeled simulation that assumes nine billion people on Earth, moderate economic growth, amelioration of environmental impacts, and some recycling of human nutrients in areas lacking sewers.

	Global, actual	Global, actual	Global, simulation	China, actual
	1970	2000	2050	2008
Year		Tg N/yr		kg N ha/yr
N inputs to global agriculture				
Fertilizer N	29	83	68	163.4
Manure N	76	101	144	52.2[b]
Human N	0	0	7	
Biologically fixed N	27	30	36	29.4
Atmospheric deposition N	27	35	44	14.0
Irrigation water N	n.d.[c]	n.d.	n.d	4.0
Total N input to agricultural land	160	249	299	280.6
Outputs				
Crop harvest/grazing	58	93	146	108.8
Ammonia volatilization	18	34	47	
Denitrification	56	82	71	111.2[d]
Leaching /runoff / erosion	28	41	36	
N loss or accumulation in the soil	—	—	—	+ 60.6

Notes: [a]Global values selected from (Bouwman et al., 2009); China values selected from Li et al.(2013) .
[b]For China livestock and human nutrients are combined.
[c]Not determined.
[d]For China all pathways of environmental N loss are combined.

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application rates designed to meet crop needs that are much higher than actually occur in most years; and (4) improving crop response knowledge, which identifies the lowest nitrogen application that is likely to produce optimum profit. These and other strategies of nutrient management will be discussed further in Chapter 16.

13.16 IMPORTANCE OF SULFUR[12]

Sulfur (S) is a macronutrient element essential for life. It is used by plants in amounts similar to those of phosphorus. Yet S often is forgotten in discussions of soil fertility management which tend to focus on N, P, and K. In addition to its vital roles in plant and animal nutrition, sulfur is also responsible for several types of air, water, and soil pollution, and is therefore of increasing environmental interest. The environmental problems associated with sulfur include acid precipitation, certain types of forest decline, acid mine drainage, acid sulfate soils, and even some toxic effects in drinking water used by humans and livestock.

Roles of Sulfur in Plants and Animals

Sulfur is a constituent of the essential amino acids methionine, cysteine, and cystine, deficiencies of which result in serious human malnutrition. As part of storage proteins, these sulfur-containing amino acids tend to accumulate in plant seeds, including grains that are staples of the human diet. The vitamins biotin, thiamine, and B1 contain sulfur, as do many protein enzymes that regulate such activities as photosynthesis and nitrogen fixation. Sulfur-to-sulfur bonds link certain sites on long chains of amino acids, causing proteins to assume the specific three-dimensional shapes that are the key to their catalytic action.

Sulfur is closely associated with nitrogen in the processes of protein and enzyme synthesis. Sulfur is also an essential ingredient of the aromatic oils that give the cabbage and onion families of plants their characteristic odors and flavors. It is not surprising that among the plants, the legume, cabbage, and onion families require especially large amounts of sulfur.

Agronomic Deficiencies of Sulfur

Depending on the plant species, healthy plant foliage generally contains 0.15–0.45% sulfur, or approximately one-tenth as much sulfur as nitrogen. Plants deficient in sulfur tend to become spindly and to develop thin stems and petioles. Their growth is slow, and maturity may be delayed. They also have a chlorotic light green or yellow appearance (Figure 13.42). Symptoms of sulfur deficiency are similar to those associated with nitrogen deficiency (see Figure 13.1). However, unlike nitrogen, sulfur is relatively immobile in the plant, so the chlorosis develops first on the youngest leaves as sulfur supplies are depleted (in nitrogen-deficient plants, chlorosis develops first on the older leaves). Sulfur-deficient leaves on some plants show interveinal chlorosis or faint striping that distinguishes them from nitrogen-deficient leaves. Also, unlike nitrogen-deficient plants, sulfur-deficient plants tend to have low sugar but high nitrate contents in their sap.

As a result of the following three independent trends, sulfur deficiencies in agricultural plants have become increasingly common during the past several decades:

1. Enforcement of clean air standards in many countries has led to reduction of sulfur dioxide (SO_2) emissions to the atmosphere from the burning of fossil coal and oil.
2. The sulfur contents of today's highly concentrated N—P—K fertilizers are far lower than those of a generation ago, resulting in less sulfur in applied amendments.
3. As crop harvests have increased, larger amounts of sulfur are being removed from the soils. Consequently, the need for sulfur has increased just as the inputs from all sources have declined.

Areas of Deficiency. Sulfur deficiencies have been reported in most areas of the world but are most prevalent in areas where soil parent materials are sandy or inherently low in sulfur,

[12]Several reviews provide more detail on the subject of sulfur in soils (Eriksen, 2009; Jez, 2008; Kovar and Grant, 2011; Scherer, 2009).

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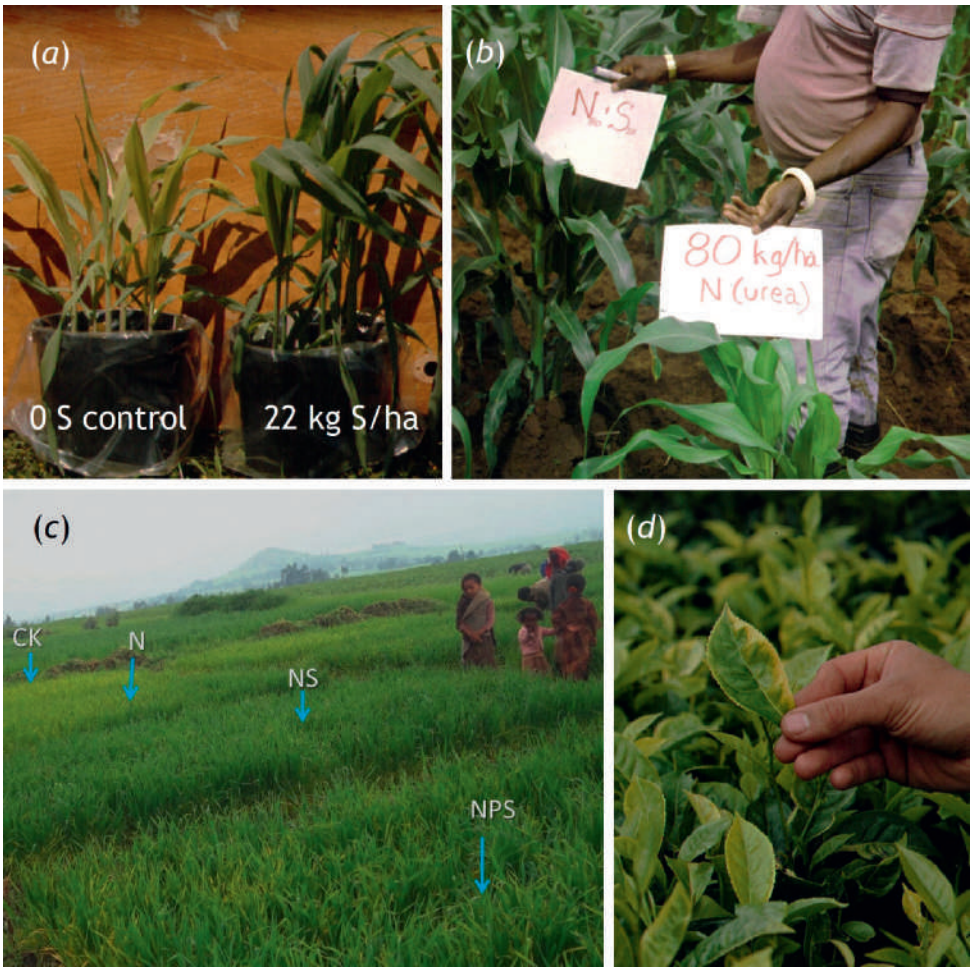

Figure 13.42 *Deficiency of sulfur is often mistaken for that of nitrogen as the plant symptoms for both include yellowish, chlorotic leaf tissue. However, S deficiency causes chlorotic leave uniformly throughout the plant or more typically the younger, uppermost leaves to become most chlorotic. This is in contrast to N deficiency which typically causes the oldest, lowest leaves on the plant to become chlorotic first. Photos (a)–(c) illustrate plant responses to S applied to soils as gypsum ($CaSO_4$). Photo (d) shows a sulfur-deficient tea bush in Malawi where this deficiency was first reported.* (Photos courtesy of Ray R. Weil)

where extreme weathering and leaching have removed this element, or where there is little replenishment of sulfur from the atmosphere. In many tropical countries, one or more of these conditions prevail and sulfur-deficient areas are common. In the industrial countries, sulfur deficiencies are most common in areas far from heavy industry, fossil fuel power plants, and large cities.

The burning of plant biomass results in a loss of sulfur to the atmosphere. In many parts of the world, crop residues and native vegetation are routinely burned as a means of clearing the land. Soils of the African savannas are particularly deficient in sulfur as a result of the annual burning of plant residues during the dry season. Fire converts much of the sulfur in the plant residues to sulfur gases, such as sulfur dioxide. Sulfur in these gases and in smoke particulates is subsequently carried by the wind hundreds of kilometers away to areas covered by rain forest, where some of the sulfur dioxide is absorbed by moist soils and foliage and some is deposited with rainfall. Thus, the soils of the savannas tend to export their sulfur to those of the rain forest (e.g., Oxisols). Consequently, the latter often contain significant accumulations of sulfur deep in their profiles (see Figure 13.43).

13.17 NATURAL SOURCES OF SULFUR

The three major natural sources of sulfur that can become available for plant uptake are: (1) *organic matter*, (2) *soil minerals*, and (3) *sulfur gases in the atmosphere.* In natural ecosystems where most of the sulfur taken up by plants is eventually returned to the same soil, these three sources combined are usually sufficient to supply the needs of growing plants (Figure 13.44).

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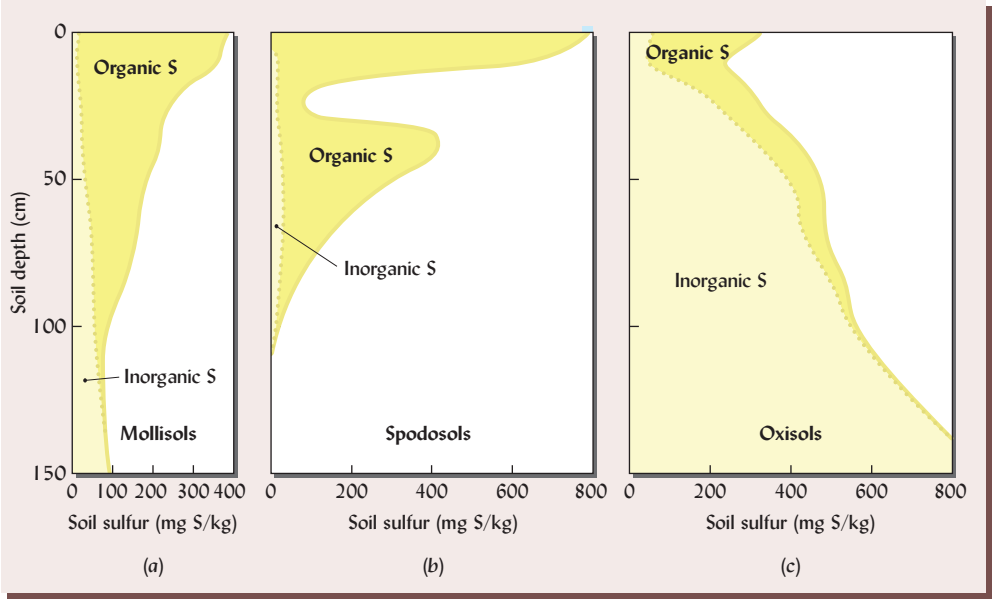

Figure 13.43 *The distribution of organic and inorganic sulfur in representative soil profiles of the soil orders (a) Mollisols, (b) Spodosols, and (c) Oxisols. In each, soil organic forms dominate the surface horizon. Considerable inorganic sulfur, both as adsorbed sulfate and calcium sulfate minerals, exists in the lower horizons of Mollisols. Relatively little inorganic sulfur exists in Spodosols. However, the bulk of the profile sulfur in the humid tropics (Oxisols) is present as sulfate adsorbed to colloidal surfaces in the subsoil.* (Diagram courtesy of Ray R. Weil)

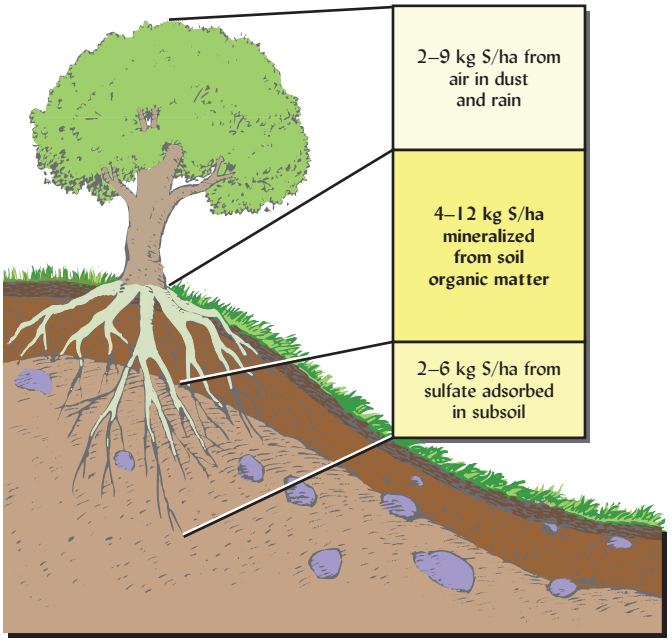

Figure 13.44 *Plants take up sulfur primarily from three sources: sulfur in atmospheric gases and dust, sulfate mineralized from soil organic matter, and sulfate adsorbed on soil minerals. Typical ranges of sulfur uptake from these sources are shown. Where these three sources are insufficient for optimal growth, the application of sulfur-containing fertilizers may be warranted. In areas downwind of coal-burning plants and metal smelters, the atmospheric contribution may be much larger than indicated here.* (Diagram courtesy of Ray R. Weil)

Organic Matter[13]

In surface soils in temperate, humid regions, 90–98% of the sulfur is usually present in organic forms (see Figure 13.43). As is the case for nitrogen, the exact forms of the sulfur in the organic matter are not well known. Recent research using sophisticated spectroscopic analyses has shown that three principal groups of organic sulfur compounds exist in SOM. The first group consists of the most reduced forms of S bonded to carbon in compounds such as sulfides, disulfides, thiols, and thiophenes. These include proteins with amino acids such as cysteine, cystine, and methionine. A second group at intermediate redox state includes sulfoxides and sulfonates in which the sulfur is bonded to carbon but also to oxygen (C—S—O). The third group consists of highly oxidized forms of S in ester sulfates (C—O—S), in which S is bound to oxygen rather than directly to carbon.

[13]For a study of organic sulfur forms in a range of soils, see Zhao et al. (2006).

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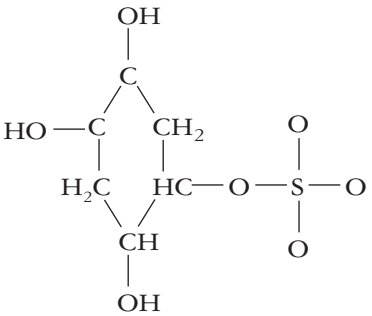
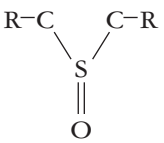
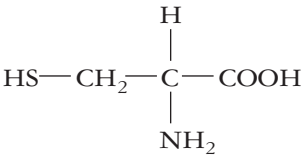
Typically, undisturbed soils under grasslands, wetlands, and moist forest vegetation have much less than half of the organic sulfur that is in the most oxidized ester-sulfate group. The ester-sulfates appear to be most prominent in well-aerated soils that have a long history of tillage.



Ester sulfate (glucose sulfate)



Sulfoxide compound



Carbon-bonded sulfur (cysteine)

Many of the S-compounds are probably somewhat protected from microbial attack by being bound to the humus and clay fractions. Compounds in the three main fractions of organic sulfur are characterized by sulfur in +6 , 0, and −2 oxidation states.

Over time, soil microorganisms break down these organic sulfur compounds into soluble forms analogous to the release of ammonium and nitrate from organic matter, discussed in Section 13.3. As with nitrogen, most soil sulfur is organic with only a very small percentage in the mineralized (sulfate) form, even in the sandy Spodosols described in Table 13.7 (compare with Figure 13.43*b*).

In dry regions, less organic matter is present in the surface soils. Therefore, the proportion of organic sulfur is not likely to be as high in arid- and semiarid-region soils as it is in humid-region soils. This is especially true in the subsoils, where organic sulfur may constitute only a small fraction of the sulfur present and where inorganic sulfur in the form of gypsum ($CaSO_4 \cdot 2H_2O$) is often present.

Table 13.7
CONCENTRATION OF SULFUR COMPOUNDS IN FORESTED SPODOSOLS
The organic layers (Oa) have high S levels and that the two organic forms (C-bonded and ester sulfate) contain 84–99% of the soil sulfur. However, the spodic horizons (Bh and Bs) can sorb significant amounts of sulfate ions.

		Proportion of soil S, %			
Horizon	Totals, μg S/g	C-bonded S	Ester sulfate	Sulfate S	Inorganic S[a]
		Huntington Forest, NY[b]			
Oa	1780	77	22	0.2	0.7
Bh	761	83	13	3.1	2.2
Bs1	527	70	22	4.2	4.4
		Conifer site[c]			
Oa	2003	88	11	0.3	0.6
Bh	540	83	11	2.4	3.4
Bs1	515	57	27	13	3.0

Notes: [a]Inorganic sulfur compounds, such as sulfides.
[b]From David et al. (1982).
[c]From Mitchell et al. (1992).

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Soil Minerals

While not as plentiful in surface soils as organic forms, inorganic sulfur compounds often supply soluble sulfur important for the nutrition of plants and soil microbes. Depending on the soil redox conditions (see Section 7.3), most inorganic sulfur is present either as sulfates (oxidized with S^{6+}) and sulfides (reduced with S^{2-}). The sulfate minerals are most easily solubilized, and the sulfate ion (SO_4^{2-}) is easily assimilated by plants. Sulfate minerals are most common in regions of low rainfall, where they accumulate in the lower horizons of some Mollisols and Aridisols (see Figure 13.43). The most common sulfate mineral, gypsum, may also accumulate when sulfate-laden soil water evaporates near the soil surface (Figure 13.45*c*). Sulfate salts may contribute to salinity in soils of arid and semiarid regions.

Sulfides are found in some humid-region wetland soils, especially those formed from marine sediments (Figure 13.45*a*). Sulfides must be oxidized to the sulfate form before the sulfur can be assimilated by plants. When waterlogged sulfide-rich soil layers are drained or exposed by excavation, oxidation will occur, and ample available sulfate-S will be released. In fact, so much sulfur may be oxidized that problems of extreme acidity result (see Section 13.20).

Another mineral source of sulfur is the clay fraction of some soils high in Fe, Al oxides, and kaolinite. These clays are able to strongly adsorb sulfate from soil solution, especially at low pH, and subsequently release it slowly by anion exchange. Oxisols and other highly weathered soils of the humid tropics and subtropics may contain large stores of sulfate sorbed in their subsoil horizons (see Figure 13.43*c*). Considerable sulfate may also be bound by the metal oxides in the spodic horizons under certain temperate and boreal forests (Table 13.7).

Atmospheric Sulfur[14]

The atmosphere contains varying quantities of carbonyl sulfide (COS), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and other sulfur gases, as well as sulfur-containing dust particles. These atmospheric forms of sulfur arise from volcanic eruptions, volatilization from soils, ocean spray, biomass fires, and industrial plants (such as metal smelters and electric-generation stations fired by high-sulfur coal). During the past century, the contribution from industrial sources has dominated sulfur deposition in certain locations.

In the atmosphere, most of the sulfur materials are eventually oxidized to sulfates, forming H_2SO_4 (sulfuric acid) and sulfate salts, such as $CaSO_4$ and $MgSO_4$. The "acid rain" problem caused by this atmospheric sulfur (as well as nitrogen) was discussed in Section 9.6 (see

Figure 13.45 *Minerals containing oxidized or reduced sulfur can commonly be found in soils, especially those soils presently or in the geologic past associated with seawater which has high levels of sulfur. (a) The bluish-black color in the interior of the clayey clod embedded in a sandy soil on the Chesapeake Bay coast of Maryland, USA, is characteristic of iron sulfide that is formed under anaerobic reducing conditions. The zones where oxidation is taking place have turned the red-orange color of oxidized iron minerals. (b) The bright yellow color on the surface of these peds along the Pacific Ocean coast in California, USA, are characteristic of the potassium–iron sulfate mineral jarosite [$KFe_3^{3+}(OH)_6(SO_4)_2$] that is an end product of the sulfur oxidation process in formerly reduced soils. (c) The whitish efflorescence of gypsum ($CaSO_4 \cdot 2H_2O$) crystals can be seen where laterally flowing groundwater evaporates from the subsoil exposed by a roadside ditch in semiarid Malawi.* (Photos courtesy of Ray R. Weil)

[14]For a discussion of global sulfur deposition trends, see Klimont et al. (2013).

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Figure 9.18). About half of the sulfur is returned to the Earth as *dry deposition* (dry particles and gases) and half as *wet deposition* (in snow and rain). Figure 13.46 shows how sulfur deposition is collected for measurement and a map of predicted global sulfur deposition.

After watching forests and lakes become seriously damaged by acid rain in the 1970s and 1980s, governments in parts of Europe and North America established regulatory programs to reduce sulfur emissions. As a result, sulfur emissions in these regions have declined by more than half since the late 1980s (although nitrogen oxide emissions have not been equally addressed). By 2008 in the eastern United States, annual sulfur deposition rarely exceeded 15 kg S/ha (= 37 kg sulfate) and was more commonly less than 6–12 kg S/ha (Figure 13.47). On the other hand, sulfur emissions are on the rise in China (until recently), India, and other newly industrializing regions, where burning of coal and oil cause as much as 50–75 kg S/ha to come down in a year. In other areas little affected by industrial emissions (e.g., most rural areas of the western United States), deposition is generally only 2–5 kg S/ha/yr. In rural Africa, as little as 1–4 kg S/ha/yr is deposited.

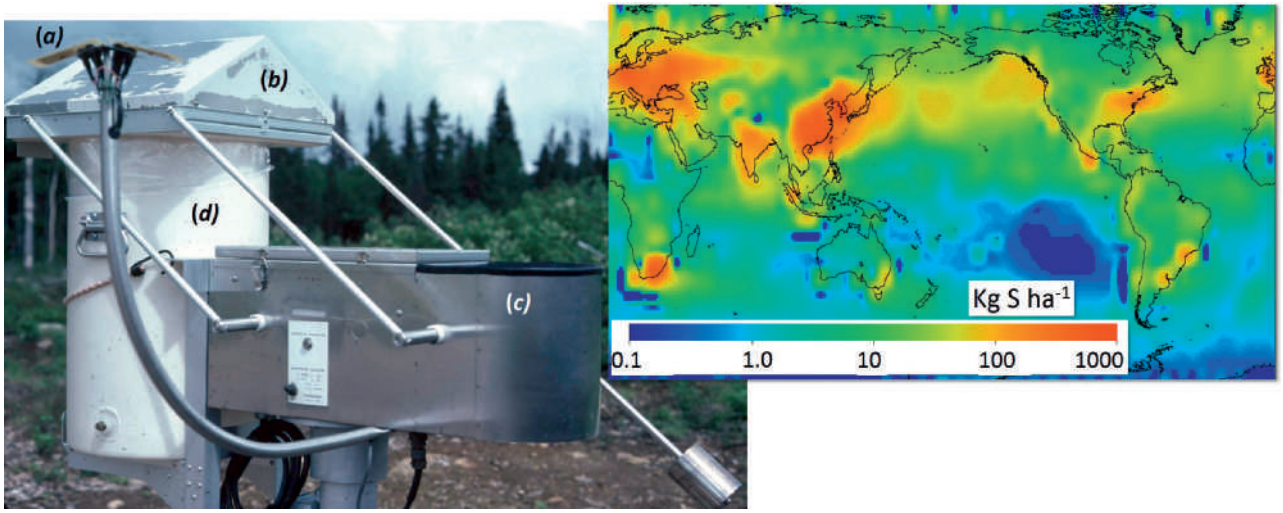
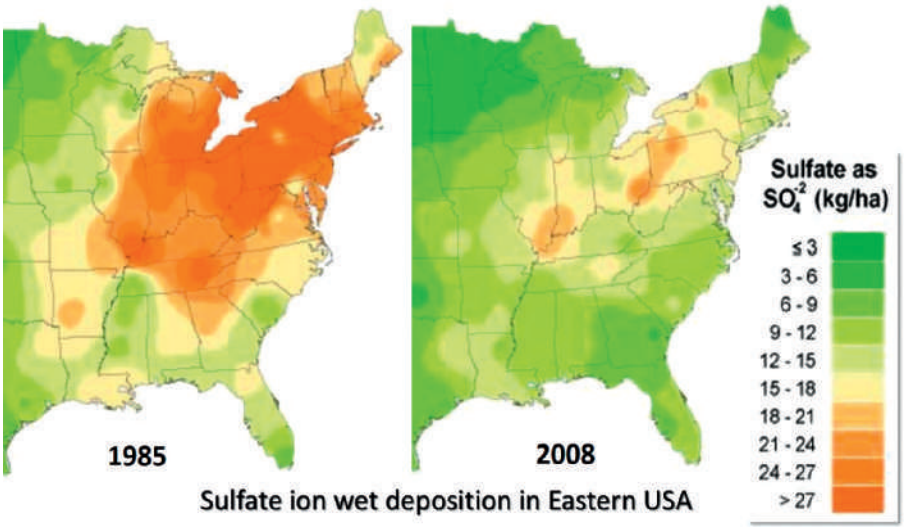


Figure 13.46 (Left) *An apparatus for collecting both wet and dry sulfur deposition. A sensor (a) triggers the small roof (b) to move over and cover the dry deposition collection chamber (c) at the first sign of rain (or snow). The wet deposition chamber (d) is then exposed to collect precipitation. When the rain ceases, the sensor triggers the roof to move back over the wet deposition collection chamber so that dry deposition can again be collected. The map shows the geographic distribution of S deposition from the atmosphere as predicted for the year 2025 based on collected data and predictive models.* (Photo courtesy of Ray R. Weil; map modified from http://www-iam.nies.go.jp/aim/aimpamph/So2emi.htm)

Figure 13.47 *The dramatic reductions in sulfur deposition achieved though environmental policies in the United States during a 23-year period.* (Modified from USEPA)



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Atmospheric sulfur becomes part of the soil–plant system mainly as SO_4^{2-} ions dissolve in soil solution, sorb to soil surfaces, or are directly absorbed by plant foliage (along with some SO_2 gas). The quantity that plants can absorb directly from the air is variable, but up to 1/3 of the sulfur in a plant may come from this source, even if available soil sulfate is adequate. In sulfur-deficient soils, about half of the plant needs can come from the atmosphere (see Figure 13.44).

The acid precipitation caused partly by atmospheric sulfur (and nitrogen) is a serious threat to the health of lakes, forests, and agroecosystems. In areas immediately downwind from industrial plants, sulfur deposition may be great enough to cause direct toxicity to trees and crops (not to mention respiratory problems in people). As far as 1000 km downwind, the deposited sulfate may mobilize toxic soil aluminum, acidify lakes, and deplete soils of needed calcium. On the other hand, recent reductions in sulfur emissions have resulted in sulfur deficiencies becoming increasingly common in some areas, especially for high-yield-potential agricultural crops. In these areas, improved sulfur recycling through cover crops and agroforestry may help provide enough of this element for high levels of crop production. Alternatively, farmers must spend more money on sulfur-fortified fertilizers and other S-containing amendments.

13.18 THE SULFUR CYCLE

The major transformations that sulfur undergoes in soils are shown in Figure 13.48. The inner circle shows the relationships among the four major forms of this element: (1) *sulfides*, (2) *sulfates*, (3) *organic sulfur*, and (4) *elemental sulfur.* The outer portions show the most important sources of sulfur and how this element is lost from the system.

Considerable similarity to the nitrogen cycle is evident (compare Figures 13.3 and 13.48). In each case, the atmosphere is an important source of the element in question. Both elements are held largely in the SOM, both are subject to microbial oxidation and reduction, both can enter and leave the soil in gaseous forms, and both are subject to some degree of leaching in the anionic form. Microbial activities are responsible for many of the transformations that determine the fates of both nitrogen and sulfur.

Figure 13.48 should be referred to frequently in conjunction with the following more detailed examination of sulfur in plants and soils.

13.19 BEHAVIOR OF SULFUR COMPOUNDS IN SOILS

Mineralization

Sulfur behaves much like nitrogen as it is absorbed by plants and microorganisms and moves through the sulfur cycle. The organic forms of sulfur must be mineralized by soil organisms if the sulfur is to be used by plants. The rate at which this occurs depends on the same environmental factors that affect nitrogen mineralization, including moisture, aeration, temperature, and pH. When conditions are favorable for general microbial activity, sulfur mineralization occurs, such that the amount of inorganic sulfur available in a soil is directly related to the amount of organic sulfur present (Figure 13.49). Some of the more easily decomposed organic compounds in the soil are sulfate esters, from which microorganisms release sulfate ions directly. However, in much of the SOM, sulfur in the reduced state is bonded to carbon atoms in protein and amino acid compounds. In the latter case the mineralization reaction might be expressed as follows:

$$\underset{\substack{\text{Proteins and}\\\text{other organic}\\\text{combinations}}}{\text{Organic sulfur}} \longrightarrow \underset{\substack{H_2S\text{ and other}\\\text{sulfides are}\\\text{simple examples}}}{\text{decay products}} \xrightarrow{O_2} \underset{\text{Sulfates}}{SO_4^{2-}} + 2H^+ \qquad (13.12)$$

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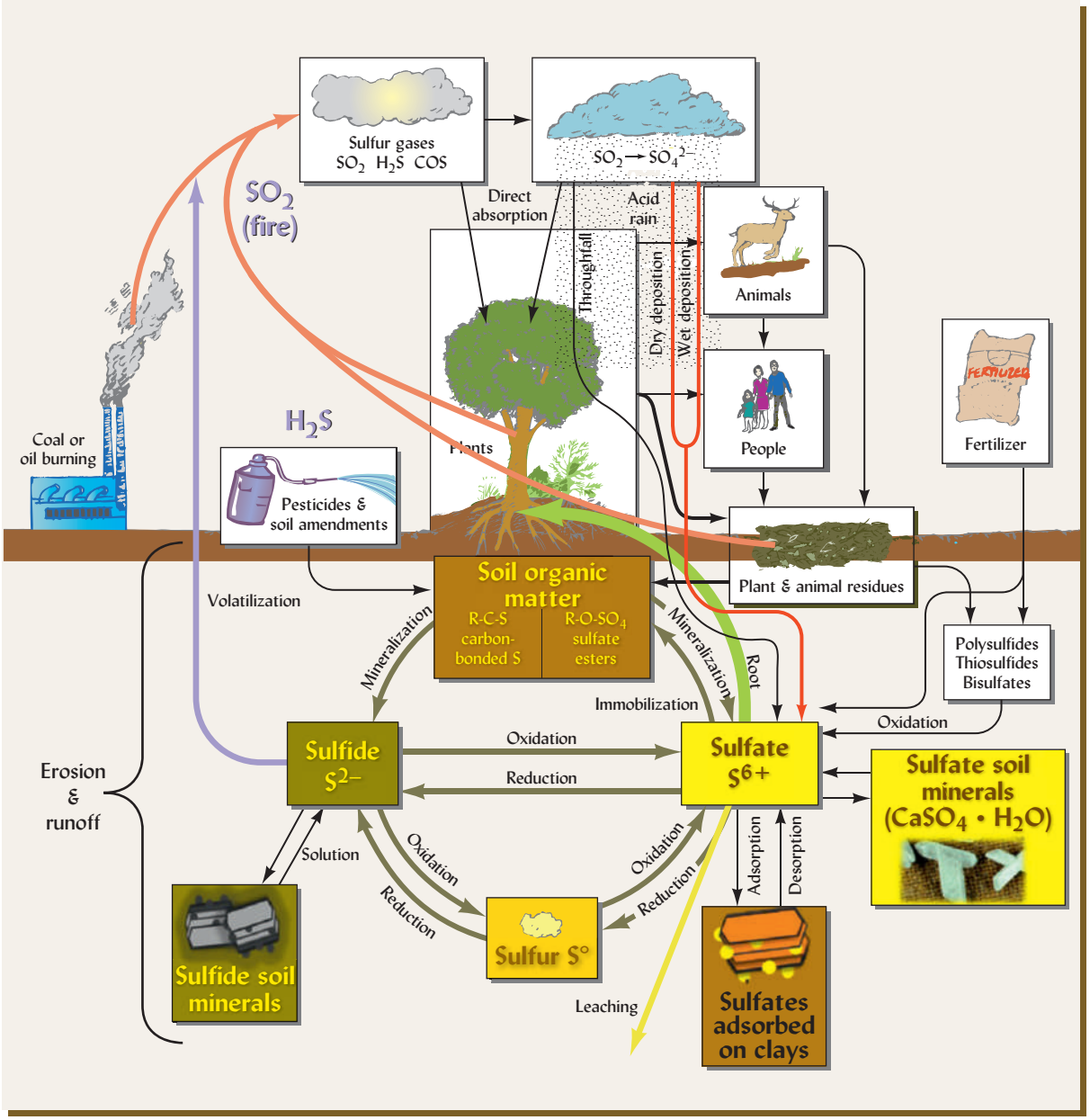

Figure 13.48 *The sulfur cycle, showing some of the transformations that occur as this element is cycled through the soil–plant–animal–atmosphere system. In the surface horizons of all but a few types of arid-region soils, the great bulk of sulfur is in organic forms. However, in deeper horizons or in excavated soil materials, various inorganic forms may dominate. The oxidation and reduction reactions that transform sulfur from one form to another are mainly mediated by soil microorganisms. Sulfur can escape into the atmosphere by microbial reduction to H_2S and by oxidation by fire to SO_2.* (Diagram courtesy of Ray R. Weil)

Because this release of available sulfate is mainly dependent on microbial processes, the supply of available sulfate in soils fluctuates with seasonal, and sometimes daily, changes in environmental conditions (Figure 13.50). These fluctuations lead to the same difficulties in predicting and measuring the amount of sulfur available to plants as were discussed in the case of nitrogen. It should be noted that for some plants, such as those in the Brassica family, a considerable amount of sulfur exists in actively growing plant tissue as sulfate or esters of sulfate that hydrolyze to chemically release soluble sulfate almost immediately when the plants are killed and added to soil as a green manure.

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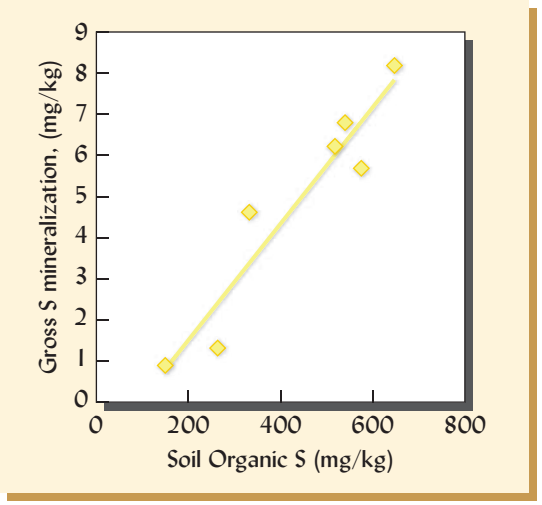

Figure 13.49 *Sulfate-S mineralized from soil organic matter in seven diverse soils in relation to the soil organic S contents. The soils ranged in texture from sandy loam to clay, in pH from 4.8 to 8.0; in organic C from 8 to 50 g/kg; and in organic C/S ratio from 103 to 54. Organic S comprised 94–99% of the total S in these A horizons, except for two clay rice paddy soils in which the organic S was 53 and 62% of the total.* [Graphed from data in Zhao et al. (2006)]

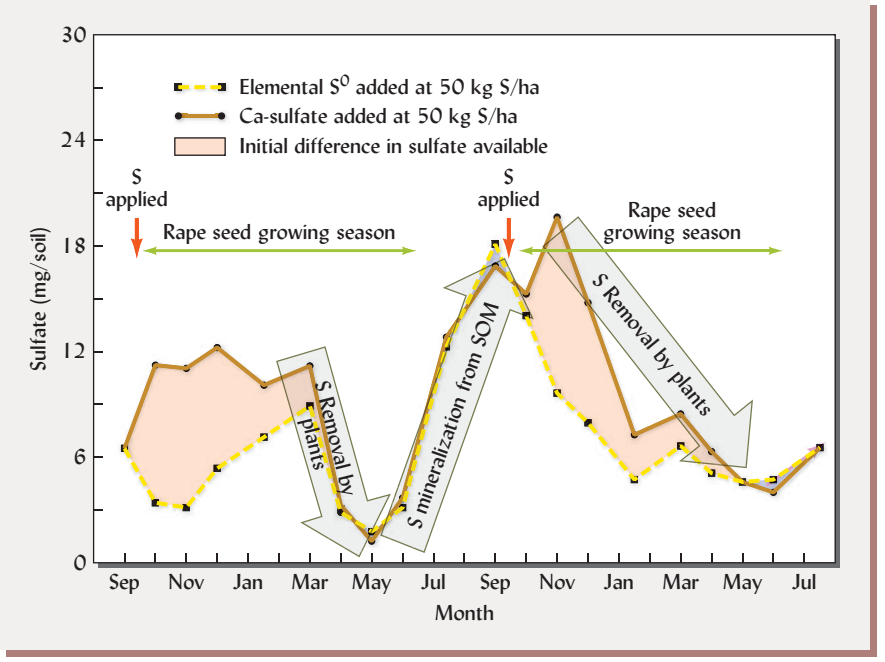

Figure 13.50 *Seasonal sulfate concentration in the surface horizon of a soil (Argixeroll, Oregon, USA) used to grow the oilseed crop, rape. This crop is sown in the fall, grows slowly during the winter, and then grows rapidly during the cool spring months. Data are shown for plots that were fertilized with either elemental S or calcium sulfate on the dates indicated by vertical arrows. Note that sulfate concentration was greater in the calcium sulfate-fertilized soils for the first few months after each application while the elemental S was slowly converted to sulfate by microbial oxidation. A distinct depression in sulfate concentration occurred each spring as the soil warmed up, stimulating both immobilization of sulfate into microbial biomass and uptake of sulfate into the rapeseed crop. Sulfate concentrations peaked in late summer and early fall, when crop uptake ceased after harvest and microbial mineralization was rapidly occurring. Movement of dissolved sulfate from the lower horizons up into the surface soil may also have occurred during hot, dry weather.* [Modified from Castellano and Dick (1991)]

Immobilization

Immobilization of inorganic forms of sulfur occurs when relatively low-sulfur, but energy-rich organic materials are added to soils. As for nitrogen—the energy-rich material stimulates microbial growth, and the inorganic nutrient (sulfate in this case) is assimilated into microbial tissue. The critical C/S ratio of organic substrates, above which generally immobilization of sulfur is likely to occur, is thought to be between 300 and 400/1 (Figure 13.51). While immobilization can draw down the sulfate concentration in the soil solution to near zero, eventually most of the carbon will be used up, the microbial activity will subside, the C/S ratio in the remaining material will drop below the critical range, and the sulfate concentrations in the soil solution will begin to rise.

The pattern of S immobilization in soils suggests that, like nitrogen, sulfur in SOM may be associated with soil organic carbon and nitrogen in a relatively constant C/N/S ratio of about 85:7:1 (Table 13.8).

During the microbial breakdown of organic materials, several sulfur-containing gases are formed, including hydrogen sulfide (H_2S), carbon disulfide (CS_2), carbonyl sulfide (COS),

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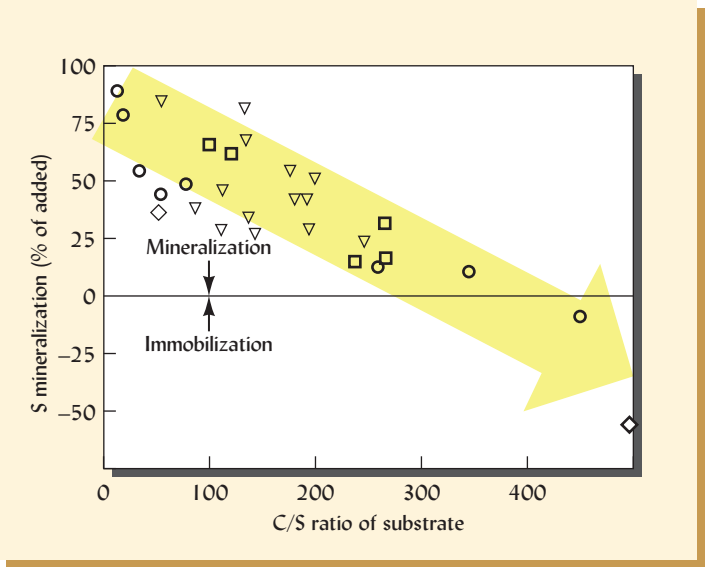

Figure 13.51 *The amount of sulfur mineralized or immobilized when organic material are added to soil is largely dependent on the C/S ratio of the added materials. The data suggest that if the C/S ratio is much above 300 or 400, net immobilization is likely. However, the release of sulfate can also be influenced by forms of sulfur (oxidized ester that easily release sulfate or more reduced C-bonded sulfur compounds) in the organic substrate.* (Data are for sewage sludge, ●, farmyard manure, ◘, and various green cover crops, ▽ (Eriksen, 2009); cabbage leaves and wheat straw, ◇ (Nziguheba et al., 2006); and rape, oat, pea wheat residues, ○ (Churka Blum et al., 2013))

Table 13.8
MEAN CARBON/NITROGEN/SULFUR RATIOS IN A VARIETY OF SOILS

Location	Description and number of soils	C/N/S ratio
North Scotland	Agricultural, noncalcareous (40)	104:7:1
Minnesota (USA)	Mollisols (6)	74:7:1
Minnesota (USA)	Spodosols (24)	108:8:1
China	Aquepts, rice paddies (2)	75:7:1
UK, New Zealand	Udalfs, Ochrepts, grass, or crops (8)	82:7:1
Eastern Australia	Acid soils (128)	126:8:1
Sweden	Agricultural, Inceptisols	69:7:1
Highland Ethiopia	Cultivated soils (3)	90:7:1
Highland Ethiopia	Forested soils (3)	67:6:1

Note: Data for China, UK, New Zealand from Zhao et al. (2006), Sweden from Kirchmann et al. (1996), for Ethiopia from Solomon et al. (2001), and for other soils from Whitehead (1964).

and methyl mercaptan (CH_3SH). All are more prominent in anaerobic soils. Hydrogen sulfide is commonly produced in waterlogged soils from reduction of sulfates by anaerobic bacteria. Most of the others are formed from the microbial decomposition of sulfur-containing amino acids and other reduced-S plant compounds. Although these gases can be adsorbed by soil colloids, some escape to the atmosphere, where they undergo chemical changes and eventually return to the soil in precipitation.

13.20 SULFUR OXIDATION AND REDUCTION

The Oxidation Process

During the microbial decomposition of organic carbon-bonded sulfur compounds, sulfides are formed along with other incompletely oxidized substances, such as elemental sulfur (S^0), thiosulfates ($S_2O_32^-$), and polythionates ($S_{2x}O_{3x}^{2-}$). These reduced substances are subject to oxidation, as

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are the ammonium compounds formed when nitrogenous materials are decomposed. The oxidation reactions may be illustrated as follows, with hydrogen sulfide and elemental sulfur:

$$H_2S + 2O_2 \longrightarrow H_2SO_4 \longrightarrow 2H^+ + SO_4^{2-} \tag{13.13}$$

$$2S + 3O_2 + 2H_2O \longrightarrow 2H_2SO_4 \longrightarrow 4H^+ + SO_4^{2-} \tag{13.14}$$

The oxidation of some sulfur compounds, such as sulfites (SO_3^{2-}) and sulfides (S^{2-}), can occur by strictly chemical reactions. However, most sulfur oxidation in soils is *biochemical* in nature, carried out by a number of autotrophic bacteria, which include five species of the genus *Thiobacillus.* Since the environmental requirements and tolerances of these five species vary considerably, the process of sulfur oxidation occurs over a wide range of soil conditions. For example, sulfur oxidation may occur at pH values ranging from <2 to >9. This flexibility is in contrast to the comparable nitrogen oxidation process, nitrification, which requires a rather narrow pH range closer to neutral.

The Reduction Process

Like nitrate ions, sulfate ions tend to be unstable in anaerobic environments. They are reduced to sulfide ions by a number of bacteria of two genera, *Desulfovibrio* (five species) and *Desulfotomaculum* (three species). The organisms use the oxygen in sulfate to oxidize organic materials. A representative reaction showing the reduction of sulfur coupled with organic matter oxidation is as follows:

$$\underset{\text{Organic alcohol}}{2R{-}CH_2OH} + \underset{\text{Sulfate}}{SO_4^{2-}} \longrightarrow \underset{\text{Organic acid}}{2R{-}COOH} + 2H_2O + \underset{\text{Sulfide}}{S^{2-}} \tag{13.15}$$

In poorly drained soils, the sulfide ion reacts immediately with iron or manganese, which in anaerobic conditions are typically present in the reduced forms. By tying up the soluble reduced iron, the formation of iron sulfides helps prevent iron toxicity in rice paddies and marshes. This reaction may be expressed as follows:

$$\underset{\substack{\text{Dissolved}\\\text{ferrous iron}}}{Fe^{2+}} + \underset{\text{Sulfide}}{S^{2-}} \longrightarrow \underset{\substack{\text{Iron sulfide}\\\text{(solid)}}}{FeS} \tag{13.16}$$

$$\underset{\substack{\text{Dissolved}\\\text{reduced}\\\text{manganese}}}{Mn^{2+}} + \underset{\text{Sulfide}}{S^{2-}} \longrightarrow \underset{\substack{\text{Manganese}\\\text{sulfide}\\\text{(solid)}}}{MnS} \tag{13.17}$$

Sulfide ions will also undergo hydrolysis to form gaseous hydrogen sulfide, which causes the rotten-egg smell of swampy or marshy areas (Figure 13.52). Sulfur reduction may take place with

Figure 13.52 *Using a handful of soil from a coastal marsh, soil scientist Robert Darmondy performs the "whiff test" he originated. The test checks for sulfidic material, which emits H_2S gas with an odor like that of a rotten egg.* (Photo courtesy of Ray R. Weil)

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sulfur-containing ions other than sulfates. For example, sulfites (SO_3^{2-}), thiosulfates ($S_2O_3^{2-}$), and elemental sulfur (S^0) are readily reduced to the sulfide form by bacteria and other organisms.

The oxidation and reduction reactions of inorganic sulfur compounds play an important role in determining the quantity of sulfate (the plant-available nutrient form of sulfur) present in soils at any one time. Also, the state of sulfur oxidation is an important factor in the acidity of soil and water draining from soils.

Acidity from Sulfur Oxidation

Reactions 13.12–13.14 show that, like nitrogen oxidation, sulfur oxidation is an acidifying process. These reactions explain why elemental sulfur and iron or sulfide can be applied to lower soil pH if it is higher than desired (see Section 10.10).

Along with nitrogen, the sulfur in the atmosphere (as described in Section 13.17) forms strong acids that acidify rainwater to a pH of 4 or even lower from the normal pH of 5.6 or higher. Section 9.6 explains how "acid rain" forms and how it damages soils, forests, and lakes in many regions. As described in Section 13.21, part of the damage to these ecosystems stems from the leaching of sulfate anions, which can promote serious losses of calcium and magnesium.

Extreme Soil Acidity. The acidifying effect of sulfur oxidation can bring about extremely acid soil conditions that cause serious soil management problems and broader environmental pollution. Certain soils and sedimentary geologic materials are termed ***sulfidic*** because they contain high levels of reduced sulfur (sulfides), usually inherited from their present or past association with seawater (which is high in sulfur). A common form of reduced sulfur is the mineral pyrite (iron disulfide, FeS_2). The sulfides in these ***potential acid-sulfate*** materials are stable so long as oxygen is not present, but if submerged or buried materials are drained or excavated, the sulfides and/or elemental sulfur quickly oxidize and form sulfuric acid, driving pH levels as low as 1.5 (see Section 9.6, Reactions 9.18 and 9.19). Plants cannot grow under these conditions (Figure 13.53). The quantity of limestone needed to neutralize the acidity is so high that it is impractical to remediate these soils by liming (for reactions, solutions, and other details see Section 9.8). If allowed to proceed unchecked, the acids may wash into nearby streams. Thousands of kilometers of streams have been seriously polluted in this manner, the water and rocks in such streams often exhibiting orange colors from the iron compounds in the acid drainage (see Figure 9.21).

Figure 13.53 *Construction of this highway cut through several layers of sedimentary rock. One of these layers contained reduced sulfide materials. Now exposed to the air and water, this layer is producing copious quantities of sulfuric acid as the sulfide materials are oxidized. Note the failure of vegetation to grow below the zone from which the acid is draining.* (Photo courtesy of Ray R. Weil)

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13.21 SULFUR RETENTION AND EXCHANGE

The sulfate anion is the form in which plants absorb most of their sulfur from soils. Since many sulfate compounds are quite soluble, the sulfate would be readily leached from the soil, especially in humid regions, were it not for its adsorption by the soil colloids. As was pointed out in Chapter 8, most soils have some anion exchange capacity that is associated with iron and aluminum oxide coatings on soil particles and, to a limited extent, with 1:1-type silicate clays. Sulfate anions are attracted by the positive charges that characterize acid soils containing these clays. They also react directly with hydroxy groups exposed on the surfaces of these clays. Figure 13.54 illustrates sulfate adsorption mechanisms on the surface of some Fe, Al oxides, and 1:1-type clays. Note that adsorption increases at lower pH values as positive charges that become more prominent on the particle surfaces attract the sulfate ions. Some sulfate reacts with the clay particles, becoming tightly bound, and is only slowly available for plant uptake and leaching.

In warm, humid regions, surface soils are typically quite low in sulfur. However, because of the anion sorption mechanisms just discussed, much sulfate may be held in the subsoil horizons of Ultisols and Oxisols of these regions (see Figure 13.43). For example, symptoms of sulfur deficiency commonly occur early in the growing season on Ultisols with sandy, low-organic-matter surface horizons. However, the symptoms may disappear as the crop matures and its roots reach the deeper horizons where sulfate is retained. In other cases the zone of sorbed sulfate occurs too deep to be accessed by the roots of most annual crops, and deep rooted perennial vegetation is needed to "pump" the sulfur to the surface soil for crop access (Figure 13.55).

Sulfate Adsorption and Leaching of Nonacid Cations

When the sulfate ion leaches from the soil, it is usually accompanied by equivalent quantities of cations, including Ca and Mg and other nonacid cations. In soils with high sulfate adsorption capacities, sulfate leaching is low and the loss of companion cations is also low (Figure 13.56). In contrast, sulfate leaching losses from low-sulfate-adsorbing soils are commonly high and take with them considerable quantities of nonacid cations. Sulfur is thus seen as an indirect conserver of these cations in the soil solution. This is of considerable importance in soils of forested areas that receive acid rain.

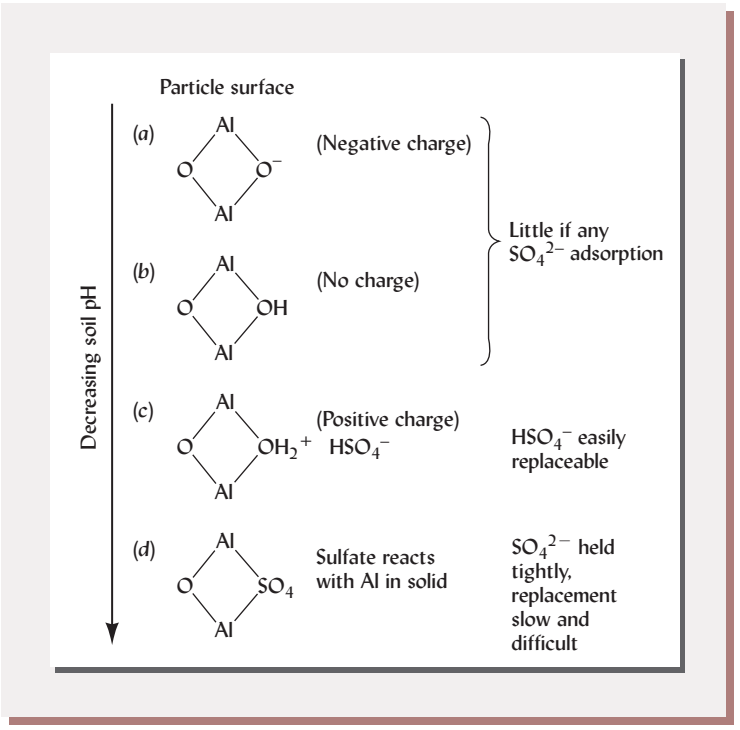

Figure 13.54 *Effect of decreasing soil pH on the adsorption of sulfates by 1:1-type silicate clays and oxides of Fe and Al (reaction with a surface-layer Al is illustrated). At high pH levels (a), the particles are negatively charged, the cation exchange capacity is high, and cations are adsorbed. Sulfates are repelled by the negative charges. As pH drops (b), the H^+ ions are attracted to the particle surface and the negative charge is satisfied, but the SO_4^{2-} ions are still not attracted. At still lower pH values (c), more H^+ ions are attracted to the particle surface, resulting in a positive charge that attracts the SO_4^{2-} ion. This is easily exchanged with other anions. At still lower pH levels, the SO_4^{2-} reacts directly with Al and becomes a part of the crystal structure. Such sulfate is tightly bound, and it is removed very slowly, if at all.* (Diagram courtesy of Ray R. Weil)

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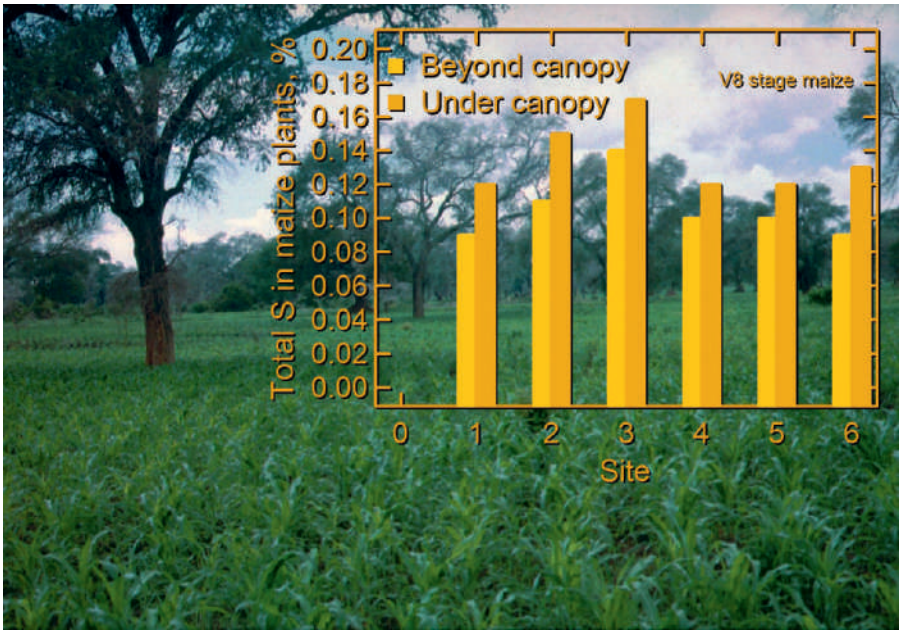

Figure 13.55 *Sulfur cycling by* Faidherbia albida *trees in an African corn-based agroforestry system. The trees are long lived with deep roots and leaves that fall off during the corn crop growing season. The trees, having translocated sulfur from sulfate sorbed deep in the subsoil, dropped their high-S content leaves to enrich the surface soil under their canopies. The darker corn under the trees appears to be a shadow from the tree, but measurements at six different sites confirmed that the darker green corn plants under the tree canopies were more vigorous and higher in S (bar graph). A similar phenomenon is illustrated in Figure 13.33 with respect to nitrate.* [Data from Weil and Mughogho (1993)]

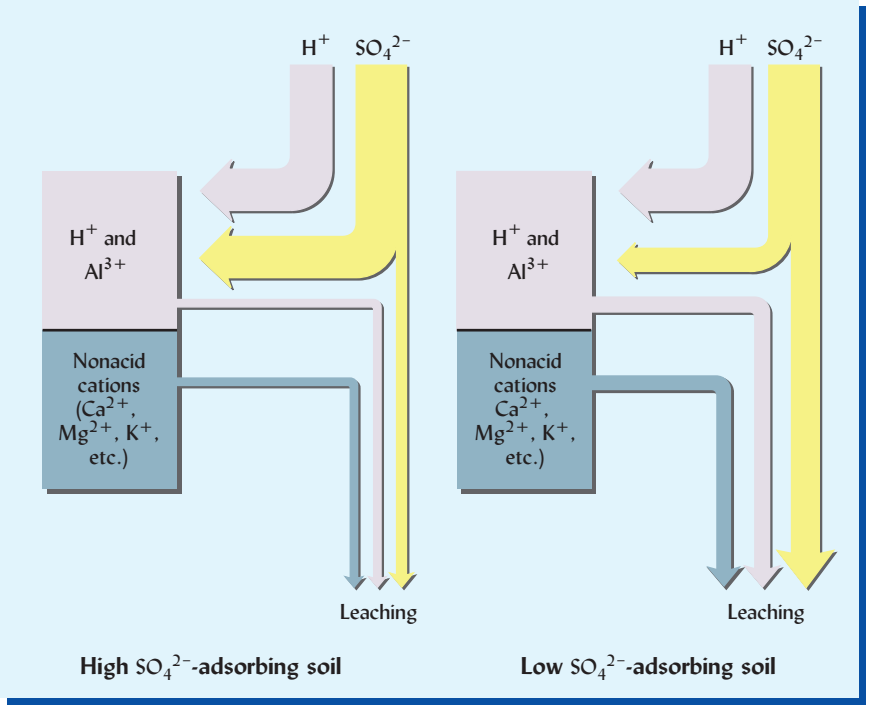

Figure 13.56 *Diagrams illustrating cation leaching losses as influenced by soil sulfate adsorption capacity. When acid rain containing SO_4^{2-} and H^+ ions falls on soils with high SO_4^{2-}-adsorbing capacities (left), the small quantities of SO_4^{2-} available for leaching are accompanied by correspondingly small amounts of cations such as Ca^{2+} and Mg^{2+}. Where acid rain falls on soils with low SO_4^{2-}- adsorbing capacity (right), most of the sulfate remains in the soil solution and is leached from the soil along with equivalent quantities of cations, including Ca^{2+} and Mg^{2+}. Al^{3+} ions that commonly replace the Ca^{2+} and Mg^{2+} lost from the soil exchange complex are toxic to many forest species. This likely accounts for at least part of the negative effects of acid rain on some forested areas.* [Redrawn from Mitchell et al. (1992)]

13.22 SULFUR AND SOIL FERTILITY MAINTENANCE

The problem of maintaining adequate quantities of sulfur for mineral nutrition of plants is becoming increasingly important. Cleaner air as a result of environmental controls along with the increasing crop removal of sulfur make it essential that farmers be attentive to prevent deficiencies of this element. In some parts of the world (especially in certain semiarid grasslands), sulfur is already the next most limiting nutrient after nitrogen, deficiencies of S being even more common than those of P and K. However, the sulfur deficiencies often go unrecognized and untreated as the plant symptoms can be mistaken for N deficiency and traditional soil testing often does not include tests for S.

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Crop residues and farmyard manures can help replenish the sulfur removed in crops, but these sources generally can help to recycle only those sulfur supplies that already exist within a farm. In regions with low-sulfur soils, greater dependence must be placed on regular applications of sulfur-containing materials. Fortunately, optimal plant growth on low-S soils can often be obtained with rather small application of about 5–15 kg S per hectare. The necessity for sulfur management will certainly increase in the future.

13.23 CONCLUSION

The cycles of sulfur and nitrogen have much in common, including many processes that operate in soils. Both elements are held by soil colloids in slowly available forms. In surface soil horizons, the bulk of both elements are found as constituents of SOM. Their release to inorganic ions (SO_4^{2-}, NH_4^+, and NO_3^-) is accomplished by soil microorganisms and makes them available to plants. Anaerobic soil organisms change both elements into gaseous forms, which are emitted to the atmosphere. While in the atmosphere, some serve as greenhouse gases that accelerate climate change. Both elements are subject to deposition from the atmosphere in the form of *acid precipitation*, seriously damaging lakes, soils, and plants in susceptible ecosystems.

Differences between nitrogen and sulfur also exist. In deeper soil layers much sulfur is found in gypsum and other sulfates (predominantly under dry climatic conditions) or pyrite and other sulfides (under low-oxygen conditions). No equivalent minerals commonly exist in soils with regard to nitrogen. Certain soil organisms have the ability to fix elemental N_2 gas into compounds usable by plants. No analogous process occurs for sulfur.

Plants remove about 10–20 times as much nitrogen as sulfur. If plant material is regularly removed from the system, it is usually more critical for nitrogen than for sulfur that the supply be regularly replenished. On the other hand, while nitrogen fertilizers are expensive and energy intensive to manufacture and are usually needed in quite large amounts (~100 kg N/ha), sulfur deficiencies can be very easily corrected with small amounts (~10 kg S/ha) of inexpensive, plentiful materials such as gypsum.

Excessive amounts of nitrogen or sulfur cause serious environmental problems. Acid deposition and acid sulfate weathering are the main environmental concerns associated with sulfur cycling in soils. Progress has been greater in reducing excesses of sulfur than of nitrogen. Nitrogen also causes acidity, but eutrophication of coastal waters by nitrogen, especially in the highly mobile nitrate form, is probably its most ecologically damaging effect. The manufacture of fertilizer, along with combustion of fossil fuels, continues to magnify these problems by swelling the Earth's total pool of reactive nitrogen.

Current knowledge of the nitrogen and sulfur cycles can help us alleviate environmental degradation and enhance life-supporting productivity. Nitrogen remains the most widely limiting—but also the most widely polluting—plant nutrient. Sulfur, whose supply to the soil was taken for granted during a century of intense industrial SO_2 emissions, is now emerging as a widely limiting nutrient for plant growth. Outside the zones of heavy sulfur deposition from air pollution, plant requirements for sulfur should be given consideration equal to phosphorus and potassium—the topics of the next chapter.

STUDY QUESTIONS

1. The manager of a landscaping company is having a bit of an argument with the landscape architect about plans to fertilize and lime the soil in a new installation before planting turf and ornamental trees. The manager planned to use mostly urea for supplying nitrogen. The landscape architect says the urea will have an alkaline reaction and raise the soil pH. The manager says that urea will have an acid reaction and lower the soil pH. Who is correct? Explain, using chemical reactions to support your argument.
2. A sandy loam soil under a golf course fairway has an organic matter content of 3% by weight. Calculate the approximate amount of nitrogen (in kg N/ha) you would expect this soil to provide for plant uptake during a typical year. Show your work and state what assumptions or estimates you made to do this calculation.
3. The grass in the fairway referred to in question #2 is mowed weekly from May through October and produces an average of 200 kg/ha dry matter in clippings each time it is mowed. The clippings contain 2.5% N

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on average (dry weight basis). How much N from fertilizer would need to be applied to maintain this growth pattern? Show your calculations and state what assumptions or estimates you made.

4. Both sulfur and nitrogen are added to soils by atmospheric deposition. In what situations is this phenomenon beneficial and under what circumstances is it detrimental?
5. About 2000 kg of wheat straw was applied to 1 ha of land. Tests showed the soil to contain 25 kg nitrate-N per ha. The straw contained 0.4% N. How much N was applied in the straw? Explain why two weeks after the straw was applied, new tests showed no detectable nitrate N. Show your work and state what assumptions or estimates you made to do this calculation.
6. Why do CAFOs (concentrated animal-feeding operations) on industrial-style farms present some environmental and health problems relating to nitrogen? What are these problems and how can they be managed?
7. What differences would you expect in nitrate contents of streams from a forested watershed and one where agricultural crops are grown, and why?
8. Microbial transformations of nitrogen involve oxidation and reduction reactions. Explain how the nitrogen from the protein in a leaf might cycle differently in a wetland soil than in an upland soil.
9. What is *acid rain*, what are the sources of acidity in this precipitation, and how does this acidity damage natural ecosystems?
10. Why might some farmers be willing to pay more for nitrogen fertilizer that contains a nitrification inhibitor chemical in it?
11. Nitrogen is said to be "fixed" from the atmosphere and is also "fixed" by vermiculite clays and humus. Differentiate between these two processes and indicate the role of microbes, if any, in each process.
12. Chemical fertilizers and manures with high N contents are commonly added to agricultural soils. Yet these soils are often lower in total N than are nearby soils under natural forest or grassland vegetation. Explain why this is the case.
13. Why are S deficiencies in agricultural crops more widespread today than 30 years ago?
14. How do riparian forests help reduce nitrate contamination of streams and rivers?
15. What are *potential acid sulfate soils*, where would you find them, and under what circumstances are they likely to cause serious problems?
16. In some tropical regions, agroforestry systems that involve mixed cropping of trees and food crops are used. What advantages in nitrogen and sulfur management do such systems have over monocropping systems that do not involve trees?

REFERENCES

Addiscott, T. M. 2005. *Nitrate, Agriculture and the Environment*. CABI Publishing, Wallingford, UK, p. 279.

Addiscott, T. M. 2006. "Is it nitrate that threatens life or the scare about nitrate?" *Journal of the Science of Food and Agriculture* **86**:2005–2009.

Baethgen, W. E., and M. M. Alley. 1987. "Nonexchangeable ammonium nitrogen contributions to plant available nitrogen." *Soil Science Society of America Journal* **51**:110–115.

Bateman, E. J., and E. M. Baggs. 2005. "Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space." *Biology and Fertility of Soils* **41**:379–388.

Bernston, G. M., and J. D. Aber. 2000. "Fast nitrate immobilization in N saturated temperate forest soils." *Soil Biology and Biochemistry* **32**:151–156.

Boesch, D. F., W. R. Boynton, L. B. Crowder, R. J. Diaz, R. W. Howarth, L. D. Mee, S. W. Nixon, N. N. Rabalais, R. Rosenberg, J. G. Sanders, D. Scavia, and R. E. Turner. 2009. "Nutrient enrichment drives Gulf of Mexico hypoxia." *Eos, Transactions American Geophysical Union* **90**:117–118.

Bouwman, A. F., A. H. W. Beusen, and G. Billen. 2009. "Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050." *Global Biogeochemical Cycles* **23**:GB0A04.

Broadbent, F. E., T. Nakashima, and G. Y. Chang. 1982. "Estimation of nitrogen fixation by isotope dilution in field and greenhouse experiments." *Agronomy Journal* **74**:625–628.

Canfield, D. E., A. N. Glazer, and P. G. Falkowski. 2010. "The evolution and future of earth's nitrogen cycle." *Science* **330**:192–196.

CAST. 1999. "Gulf of Mexico hypoxia: Land and sea interactions." Task Force Report 134. Council for Agricultural Science and Technology, Ames, IA.

Castellano, S. D., and R. P. Dick. 1991. "Cropping and sulfur fertilization influence on sulfur transformations in soil." *Soil Science Society of America Journal* **54**:114–121.

Churka Blum, S., J. Lehmann, D. Solomon, E. F. Caires, and L. R. F. Alleoni. 2013. "Sulfur forms in organic substrates affecting S mineralization in soil." *Geoderma* **200–201**:156–164.

David, M. B., M. J. Mitchell, and J. P. Nakas. 1982. "Organic and inorganic sulfur constituents of a forest soil and their relationship to microbial activity." *Soil Science Society of America Journal* **46**:847–852.

Eriksen, J. 2009. "Soil sulfur cycling in temperate agricultural systems." *Advances in Agronomy* **102**:55–89.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett,

FOR REFERENCE PURPOSES ONLY

S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman, and D. P. M. Zaks. 2011. "Solutions for a cultivated planet." *Nature* **478**:337–342.

Fowler, D., C. Steadman, D. Stevenson, M. Coyle, R. Rees, U. Skiba, M. Sutton, J. Cape, A. Dore, and M. Vieno. 2015. "Effects of global change during the 21st century on the nitrogen cycle." *Atmospheric Chemistry and Physics Discussions* 15:1747–1868.

Franzen, D. W. 2004. "Volatilization of urea affected by temperatures and soil pH." North Dakota State University Extension Service. http://www.ag.ndsu.edu/procrop/fer/ureavo05.htm.

Galloway, J. N., and E. B. Cowling. 2002. "Reactive nitrogen and the world: 200 years of change." *Ambio* **31**:64–71.

Gentry, L. F., M. L. Ruffo, and F. E. Below. 2013. "Identifying factors controlling the continuous corn yield penalty." *Agronomy Journal* **105**:295–303.

Glibert, P., J. Harrison, C. Heil, and S. Seitzinger. 2006. "Escalating worldwide use of urea: A global change contributing to coastal eutrophication." *Biogeochemistry* **77**:441–463.

Gruber, N., and J. N. Galloway. 2008. "An earth-systems perspective of the global nitrogen cycle." *Nature* **451**:293–296.

Guillard, K., and K. L. Kopp. 2004. "Nitrogen fertilizer form and associated nitrate leaching from cool-season lawn turf." *Journal of Environmental Quality* **33**:1822–1827.

Hanson, G. C., P. M. Groffman, and A. J. Gold. 1994. "Denitrification in riparian wetlands receiving high and low groundwater nitrate inputs." *Journal of Environmental Quality* **23**:917–922.

Heckman, J. R., H. Lui, W. Hill, M. Demilia, and W. L. Anastasai. 2000. "Kentucky bluegrass responses to mowing practice and nitrogen fertility management." *Journal of Sustainable Agriculture* **15**:25–33.

Holcomb, J. C., D. M. Sullivan, D. A. Horneck, and G. H. Clough. 2011. "Effect of irrigation rate on ammonia volatilization." *Soil Science Society of America Journal* **75**:2341–2347.

Ishikawa, T., G. V. Subbarao, O. Ito, and K. Okada. 2003. "Suppression of nitrification and nitrous oxide emission by the tropical grass *Brachiaria humidicola*." *Plant Soil* **255**:413–419.

Jez, J. (ed.). 2008. *Sulfur: A Missing Link Between Soil, Crops and Nutrition*. American Society of Agronomy, Madison, WI, pp. 1–323.

Kennedy, I. R., A. T. M. A. Choudhury, and M. L. Kecskes. 2004. "Non-symbiotic bacterial diazotrophs in crop-farming systems: Can their potential for plant growth promotion be better exploited?" *Soil Biology Biochemistry* **36**:1229–1244.

Khalil, K., B. Mary, and P. Renault. 2004. "Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration." *Soil Biology Biochemistry* **36**:687–699.

Kirchmann, H., F. Pichlmayer, and M. H. Gerzabek. 1996. "Sulfur balances and sulfur-34 abundance in a long-term fertilizer experiment." *Soil Science Society of America Journal* **60**:174–178.

Klemmedson, J. O. 1994. "New Mexican locust and parent material: Influence on forest floor and soil macronutrients." *Soil Science Society of America Journal* **58**:974–980.

Klimont, Z., S. J. Smith, and J. Cofala. 2013. "The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions." *Environmental Research Letters* **8**:014003.

Kovar, J. L., and C. A. Grant. 2011. "Nutrient cycling in soils: Sulfur." In J. L. Hatfield, and T. J. Sauer (eds.). *Soil Management: Building a Stable Base for Agriculture*. Soil Science Society of America, Madison, WI, USA, pp. 103–115.

Lambert, K. F., and C. Driscoll. 2003. "Nitrogen pollution: From the sources to the sea." *Science Links Publication*, Vol. 1(2). Hubbard Brook Research Foundation, Hanover, NH.29. http://www.hubbardbrook.org/hbrf/nitrogen/Nitrogen.pdf.

Leffelaar, P. A., and W. W. Wessel. 1988. "Denitrification in a homogeneous, closed system: Experimental and simulation." *Soil Science* **146**:335–349.

L'hirondel, J., and J.-L. L'hirondel. 2002. *Nitrate and Man: Toxic, Harmless or Beneficial?* CABI, Wallingford, UK, p. 168.

Li, S., P. He, and J. Jin. 2013. "Nitrogen use efficiency in grain production and the estimated nitrogen input/output balance in China agriculture." *Journal of the science of food and agriculture* 93:1191–1197.

Magill, A. H., J. D. Aber, W. S. Currie, K. J. Nadelhoffer, M. E. Martin, W. H. Mcdowell, J. M. Melillo, and P. Steudler. 2004. "Ecosystem response to 15 years of chronic nitrogen additions at the Harvard forest LTER, Massachusetts, USA." *Forest Ecology and Management* **196**:7–28.

Mallin, M. A., and T. L. Wheeler. 2000. "Nutrients and fecal coliform discharge from coastal North Carolina golf courses." *Journal of Environmental Quality* **29**:979–986.

Mekonnen, K., R. Buresh, and B. Jama. 1997. "Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields." *Plant and Soil* **188**:319–327.

Mitchell, M. J., M. B. David, and R. B. Harrison. 1992. "Sulfur dynamics of forest ecosystems." In R. W. Howarth, J. W. B. Stewart, and M. V. Ivanov (eds.). *Sulfur Cycling on the Continents*, 1992 SCOPE. Wiley, New York.

Morford, S.L., B.Z. Houlton, and R.A. Dahlgren. 2011. "*Increased forest ecosystem carbon and nitrogen storage from nitrogen rich bedrock." Nature* 477:78-81.

Mueller, N.D., P.C. West, J.S. Gerber, G.K. MacDonald, S. Polasky, and J.A. Foley. 2014. *"A tradeoff frontier for global nitrogen use and cereal production."* Environmental Research Letters **9**:054002.

Nziguheba, G., E. Smolders, and R. Merckx. 2006. "Mineralization of sulfur from organic residues assessed by

FOR REFERENCE PURPOSES ONLY

inverse isotope dilution." *Soil Biology and Biochemistry* **38**:2278–2284.

Omay, A., C. Rice, D. Maddux, and W. Gordon. 1998. "Corn yield and nitrogen uptake in monoculture and in rotation with soybean." *Soil Science Society of America Journal* **62**: 1596–1603.

Patrick, W. H., Jr. 1982. "Nitrogen transformations in submerged soils." In F. J. Stevenson (ed.). *Nitrogen in Agricultural Soils*, Agronomy Series No. 27. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Qiao, C., L. Liu, S. Hu, J.E. Compton, T.L. Greaver, and Q. Li. 2015. "How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input." *Global Change Biology* 21:1249-1257.

Ros, G. H., E. Hoffland, C. van Kessel, and E. J. M. Temminghoff. 2009. "Extractable and dissolved soil organic nitrogen – a quantitative assessment." *Soil Biology and Biochemistry* **41**:1029–1039.

Sanchez, P.A., R.J. Buresh, and R.R. Leakey. 1997. "*Trees, soils, and food security*". Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 352:949–961.

Santamaria, P. 2006. "Nitrate in vegetables: Toxicity, content, intake and EC regulation." *Journal of the Science of Food and Agriculture* **86**:10–17.

Santi, C., D. Bogusz, and C. Franche. 2013. "Biological nitrogen fixation in non-legume plants." *Annals of Botany* **111**:743–767.

Scheer, C., S. J. Del Grosso, W. J. Parton, D. W. Rowlings, and P. R. Grace. 2014. "Modeling nitrous oxide emissions from irrigated agriculture: Testing DayCent with high frequency measurements." *Ecological Applications* **24**: 528–538.

Scherer, H. W. 2009. "Sulfur in soils." *Journal of Plant Nutrition and Soil Science* **172**:326–335.

Science Advisory Board-USEPA. 2011. "Reactive nitrogen in the United States: An analysis of inputs, flows, consequences, and management options. EPA -SAB-11-013." A Report of the EPA Science Advisory Board. http://www.epa.gov/sab.

Solomon, D., J. Lehmann, M. Tekalign, F. Fritzsche, and W. Zech. 2001. "Sulfur fractions in particle-size separates of the sub-humid Ethiopian highlands as influenced by land use changes." *Geoderma* **102**:41–59.

Stivers, L. J., C. Shennen, E. Jackson, K. Groody, and C. J. Griffin. 1993. "Winter cover cropping in vegetable production systems in California." In M. G. Paoletti, et al. (eds.). *Soil Biota, Nutrient Cycling and Farming Systems*. Lewis Press, Boca Raton, FL.

Suwanwaree, P., and G. P. Robertson. 2005. "Methane oxidation in forest, successional, and no-till agricultural ecosystems: Effects of nitrogen and soil disturbance." *Soil Science Society of America Journal* **69**:1722–1729.

Thamdrup, B. 2012. "New pathways and processes in the global nitrogen cycle." *Annual Review of Ecology, Evolution, and Systematics* **43**:407–428.

USDA/NRCS. 2012. "Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River Basin." Conservation Effects Assessment Project. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

van Kessel, C., T. Clough, and J. W. van Groenigen. 2009. "Dissolved organic nitrogen: An overlooked pathway of nitrogen loss from agricultural systems?" *Journal of Environmental Quality* **38**:393–401.

van Niftrik, L., and M. S. M. Jetten. 2012. "Anaerobic ammonium-oxidizing bacteria: Unique microorganisms with exceptional properties." *Microbiology and Molecular Biology Reviews* **76**:585–596.

Weil, R. R., and S. K. Mughogho. 1993. "Nutrient cycling by *Acacia albida* (syn. *Faidherbia albida*) in agroforestry systems." In E. A. Ragland (ed.). *Technologies for Sustainable Agriculture in the Tropics*. American Society of Agronomy, Madison, WI, pp. 97–108.

Whitehead, D. C. 1964. "Soil and plant nutrition aspects of the sulfur cycle." *Soils and Fertilizers* **27**:1–8.

Yang, Y., M. Zhang, Y. Li, X. Fan, and Y. Geng. 2013. "Controlled-release urea commingled with rice seeds reduced emission of ammonia and nitrous oxide in rice paddy soil." *Journal of Environmental Quality* **42**:1661–1673.

Zhao, F. J., J. Lehmann, D. Solomon, M. A. Fox, and S. P. McGrath. 2006. "Sulphur speciation and turnover in soils: Evidence from sulphur k-edge XANES spectroscopy and isotope dilution studies." *Soil Biology and Biochemistry* **38**:1000–1007.

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Decaying bones slowly return phosphorus to the soil. (Ray R. Weil)

14 Soil Phosphorus and Potassium

No sólo son raíces bajo las piedras teñidas de sangre, no sólo sus pobres huesos derribados definitivamente trabajan en la tierra . . .
(They are not only roots beneath the bloodstained stones, not only do their poor demolished bones definitely till the soil . . .)
—*Pablo Neruda, Chilean poet,* España en Corazon (Spain in Our Hearts)

Among the nutrient elements, phosphorus[1] is second only to nitrogen in its impact on the productivity and health of terrestrial and aquatic ecosystems. The total quantity of phosphorus in most native soils is low, with most of what is present in forms quite unavailable to plants. Phosphorus is so scarce in natural ecosystems that archaeologists often test soils for the presence of high phosphorus concentrations as an indication of prehistoric human habitations.

We shall see that natural ecosystems have evolved ways of maximizing the efficiency with which plants use and recycle limited phosphorus supplies. Historically, agricultural land uses have accelerated the loss and removal of phosphorus without encouraging its recycling and replacement. Low phosphorus availability in agricultural soils often leads to major social and environmental problems. Unproductive soils fail to produce adequate crops, forcing poor people to clear more land in order to produce enough food to survive. The cleared land supports little vegetative cover and so is subject to erosion that further degrades the soils and pollutes rivers and lakes with sediment-laden runoff. This scenario pertains today in much of sub-Saharan Africa, where phosphorus-deficient soils and inadequate supplies of phosphorus fertilizers have contributed to this being the main region of the world where food supplies remain insecure.

Industrialized countries have for many years overcompensated for initial low phosphorus availability by adding far more phosphorus to agricultural soils than removed in crop harvests. Excessive application of phosphorus-containing fertilizers and concentration of livestock and their organic wastes have led to phosphorus building up in the surface soils of many agricultural watersheds. Phosphorus-laden runoff water from such watersheds, along with the runoff and sewage flows from urban watersheds, constitutes one of the most serious types of water pollution. This pollution is especially damaging to freshwater ecosystems in estuaries, lakes, and streams in which it can jeopardize drinking water supplies and restrict the use of aquatic resources for fisheries, industry, and recreation. Control of this *nutrient cum pollutant* is therefore a high priority for national and regional water quality programs.

Potassium does not play as direct a role in water quality as phosphorus, but inadequate supplies of this element commonly limit plant productivity and crop quality. Even though most soils have large total supplies of this element, most of that present is tied up as insoluble minerals and is only slowly available for plant use. Plants require potassium

[1]For a fascinating historical account about all aspects of this element, see Emsley (2002). For a readable reviews of environmental, biogeochemical, agricultural, and social aspects of phosphorus, see Butusov and Jernelöv (2013).

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in much larger amounts than phosphorus, so careful management practices are necessary to ensure sufficient short- and long-term availability of this nutrient for vigorous plant growth.

In this chapter we will learn how to optimize plant availability of both potassium and phosphorus, as well as how to minimize the pollution potential of the latter. We will begin with phosphorus.

14.1 PHOSPHORUS IN PLANT NUTRITION AND SOIL FERTILITY[2]

Neither plants nor animals can live without phosphorus. It is an essential component of the organic compound **adenosine triphosphate** (ATP), which is the *energy currency* that drives most biochemical processes. For example, the uptake of nutrients and their transport within the plant, as well as their assimilation into different biomolecules, are energy-using plant processes that require ATP.

Phosphorus, like nitrogen, is literally "in our DNA." It is an essential component of **deoxyribonucleic acid** (DNA), the seat of genetic inheritance, and of **ribonucleic acid** (RNA), which directs protein synthesis in both plants and animals. Phospholipids, which play critical roles in cellular membranes, are another class of universally important phosphorus-containing compounds. Bones and teeth are made of the calcium-phosphate compound apatite. In fact, ground bone (called bone meal) has been widely used as a phosphorus fertilizer. In healthy plants, leaf tissue phosphorus content is usually about 0.2–0.4% of the dry matter, about 1/10th the comparable levels for nitrogen.

Phosphorus and Plant Growth

Aspects of Plant Growth Enhanced. Adequate phosphorus nutrition enhances the fundamental processes of photosynthesis, flowering, fruiting (including seed production), and maturation. Phosphorus is needed in especially large amounts for cell division and growth in meristematic tissues. Root growth, particularly development of lateral roots and fibrous rootlets, is encouraged by phosphorus. Good supplies of phosphorus are essential for efficient biological nitrogen fixation, and the resulting growth and protein content of leguminous plants, most notably forages and such staple sources of protein on human diets as soybeans, peas, and beans.

Symptoms of Phosphorus Deficiency in Plants. A phosphorus-deficient plant is usually stunted, thin-stemmed, and spindly, but its foliage, rather than being pale, is often dark, almost bluish-green. Thus, unless much larger, healthy plants are present to make a comparison, phosphorus-deficient plants often seem quite normal in appearance (Figure 14.1*a–c*). Phosphorus-deficient plants are also characterized by delayed maturity, sparse flowering, and poor seed quality. In severe cases, phosphorus deficiency can cause yellowing and senescence of leaves. Many plants develop purple colors in their leaves and stems (Figure 14.1*d–g*) as a result of phosphorus deficiency. Related stresses, such as cold temperatures, can also cause purple pigmentation. Phosphorus is very mobile within the plant, being transferred from older to younger leaves when in short supply. Therefore, older leaves show deficiency symptoms first.

The Phosphorus Problem in Soil Fertility

Phosphorus presents a soil fertility problem in three ways. *First*, the total phosphorus content of soils (Figure 14.2) is relatively low, ranging from 500 to 10,000 kg P in the upper 50 cm of 1 ha of soil. *Second*, the phosphorus compounds commonly found in soils are mostly unavailable for plant uptake, often because they are highly insoluble. *Third*, when soluble sources of phosphorus, such as those in fertilizers and manures, are added to soils, they may become fixed (changed to unavailable forms) and in time form highly insoluble compounds (see Section 14.8).

Fixation[3] reactions in low-P soils may allow only a small fraction (10–15%) of the phosphorus applied in fertilizers and manures to be taken up by plants in the year of application.

[2]For a review of the plant availability of this element, see Sharpley (2000).

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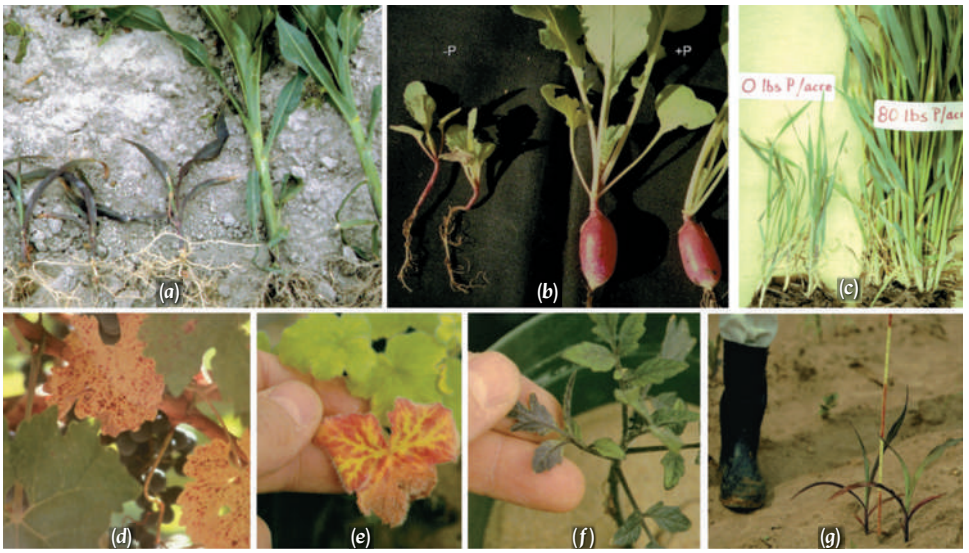

Figure 14.1 *Plant symptoms indicative of phosphorus deficiency. In (a)–(c), P-deficient corn, radish, and cereal rye plants are shown next to plants fertilized with adequate P. Severe stunting (g), sometimes with no special foliar symptoms (b) is typical. Reduction in root carbohydrate storage (b) is also common. In (d)–(g), grape, geranium, tomato, and corn, respectively, exhibit red or purple colors produced by P-deficiency, especially on leaf sheathes and the underside of older leaves.* (Photos courtesy of Ray R. Weil)

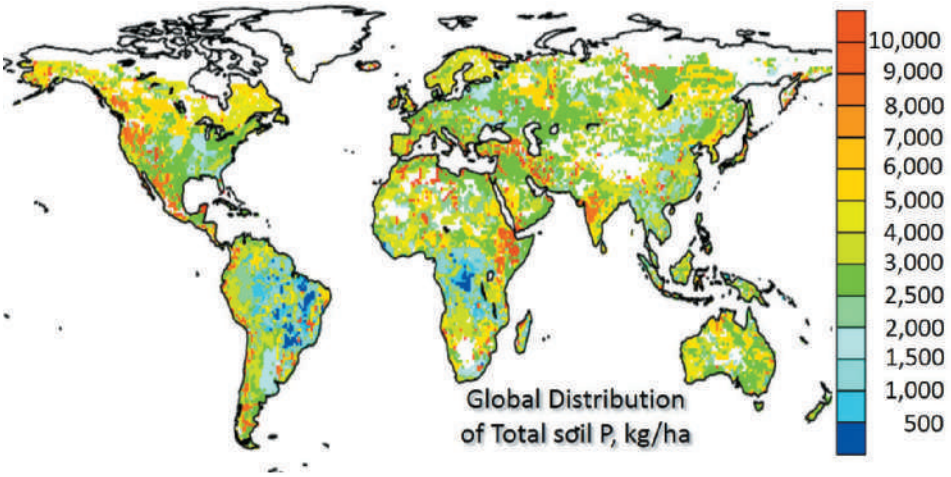

Figure 14.2 *Total phosphorus levels in the upper 50 cm of the world's soils range from less than 500 kg/ha in highly weathered soils in the humid tropics as high as 10,000 kg/ha in some young little-weathered soils mainly in mountainous or desert regions. The model used to make this map estimates the global total soil P to 50 cm depth as 40.6 Pg P.* [Modified from Yang et al. (2013)]

Consequently, for many years, farmers in developed countries who could afford to do so typically applied two to four times as much phosphorus as was removed in the crop harvest. Over time, such practices saturated the phosphorus-fixation capacity and built up the level of available soil phosphorus. Such long-term buildup of phosphorus certainly improves soil fertility. However, to avoid the environmental damages discussed in Section 14.2, little or no additional phosphorus should be applied until soil phosphorus is drawn down to more moderate levels over a period of years. Fertilizer use trends show that phosphorus application rates in developed countries (e.g., countries in Europe and USA) have leveled off or declined in recent decades reflecting the fact that less fertilizer is needed where soil phosphorus levels have been built up (Figure 14.3). Trends show that in emerging economies (e.g., many countries in Asia and South America), phosphorus fertilizer use began to overcome P limitations in agricultural soils in the 1980s and 1990s. In these countries, phosphorus use has continued to increase, suggesting a potentially polluting phosphorus-fertility "overshoot" even more severe than what occurred in Europe several decades earlier.

[3]Note that the term *fixation* as applied to phosphorus has the same general meaning as the chemical fixation of potassium or ammonium ions; that is, the chemical being fixed is bound, entrapped, or otherwise held tightly by soil solids in a form that is relatively unavailable to plants. In contrast, the fixation of gaseous nitrogen refers to the *biological* conversion of N_2 gas to reactive forms that plants can use.

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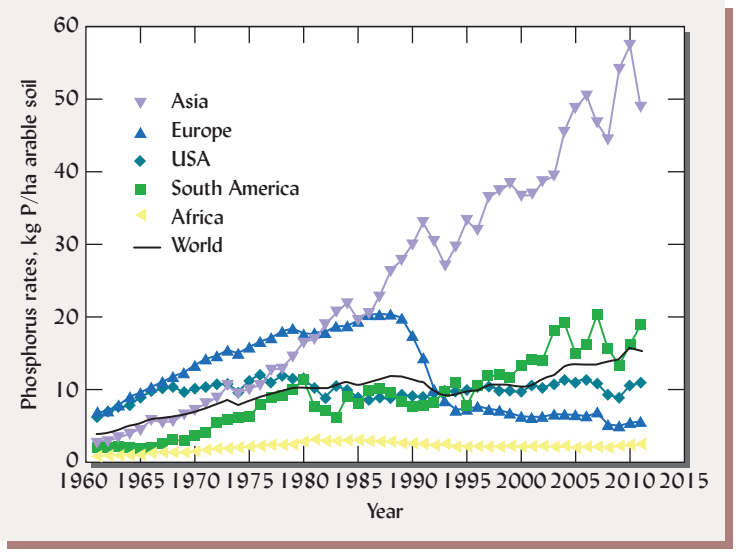

Figure 14.3 *Historical trends for rates of phosphorus fertilizer use in various parts of the world. Note that around 1960, developed countries (here Europe and USA are shown) used 2–10 times as much P per hectare of arable land as developing countries in Asia, Africa, and South America. By the late 1990s, the relationship was reversed, except for Africa. The excessively high rates of P application in Asia since the 1980s are largely driven by use and over-use in China.* [Graphed from data at FAO (2014)]

In the poorest countries, especially in Africa, where most farmers cannot afford to buy fertilizer, underuse rather than overuse of fertilizer phosphorus is the rule. In most of sub-Saharan Africa, per-capita food production has stagnated or declined in recent decades and fertilizer additions to food crops supply only a small fraction of the amount of phosphorus removed in the harvest. Soils there are depleted of phosphorus year after year, such that in many areas, lack of this element is among the most limiting factors in food-crop production (Figure 14.4*b*). Food security in sub-Saharan Africa will not likely be achieved until the critical phosphorus deficiency problems are solved.

14.2 EFFECTS OF PHOSPHORUS ON ENVIRONMENTAL QUALITY[4]

Two major global environmental problems related to soil phosphorus are *degradation of land* caused by *too little* available phosphorus and *degradation of water* with **accelerated eutrophication** caused by *too much* phosphorus. Both problems are related to the role of phosphorus as a plant nutrient.

Land Degradation

Many highly weathered soils in the warm, humid, and subhumid regions of the world have very little capacity to supply phosphorus for plant growth. The low phosphorus availability is partly a result of low levels of total phosphorus remaining in these soils after long periods of intense weathering (Figure 14.2) and partly due to the low availability of phosphorus in the aluminum and iron compounds that are the dominant forms of phosphorus in these soils (Section 14.5). Undisturbed natural ecosystems in these regions usually contain enough phosphorus in the plant biomass and soil organic matter to maintain a substantial standing crop of forest vegetation. Most of the phosphorus taken up by the plants is that which was released from the decomposing residues of other plants. Very little is lost as long as the system remains undisturbed.

Once the forest is cleared (by timber harvest, by forest fires, or for agriculture), the losses of phosphorus in eroded soil particles, in runoff water, and in biomass removals (harvests) can be substantial. Within just a few years, the system may lose most of the phosphorus that had been cycling between the plants and the soils. The remaining inorganic phosphorus in the soil is largely unavailable for plant uptake. In this manner, the phosphorus-supplying capacity of

[4]For an excellent set of research and review papers on practical and innovative measures to control losses of phosphorus from agricultural lands, see *Journal of Environmental Quality* **29**:1–181, 2000. For a forward-thinking approaches to problems of soil phosphorus in Africa, see Buresh et al. (1997) and Sanchez (2002).

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Figure 14.4 *On highly weathered soils in the tropics and subtropics, low availability of phosphorus can limit the regrowth of natural vegetation or the production of crops after natural vegetation is cleared. (a) Several years after this Caribbean rain forest was disturbed by a landslide, lack of sufficient soil phosphorus is still inhibiting the regrowth of vegetation within the demarcated unfertilized plot. The surrounding area was fertilized with phosphorus shortly after the landslide. (b) Phosphorus has been so depleted in this African cornfield that the woman will have little or no grain to harvest from her severely phosphorus-deficient crop. In both cases, stunted plant growth leaves the soil susceptible to accelerated erosion and further degradation.* (Photos courtesy of Ray R. Weil)

the disturbed soil rapidly becomes so low that regrowth of natural vegetation is sparse, and, on land cleared for agricultural use, crops soon fail to produce useful yields (Figure 14.4).

Leguminous plants that might be expected to replenish soil nitrogen supplies and enhance ecosystem diversity and productivity are particularly hard-hit by phosphorus deficiency. The growth, nodulation, and N_2-fixation by legume plants, including forest trees, may be dramatically inhibited by very low levels of soil phosphorus (Figure 14.5). Therefore, differences in soil conservation or small additions of P fertilizer can be leveraged to enhance nitrogen supplies and promote major increases in ecosystem diversity and productivity.

Without sufficient P, spindly plants, deficient in both phosphorus and nitrogen, will provide little vegetative cover to prevent heavy rains from washing away the surface soil. The resulting erosion will further reduce soil fertility and water-holding capacity. Such increasingly impoverished soils can support less and less vegetative cover, and so the degradation accelerates. Meanwhile, the soil particles lost by erosion become sediment farther down in the watershed, filling in reservoirs, increasing the turbidity of the rivers, and choking lakes and estuaries with algae (see Chapter 17).

Phosphorus deficiency limits growth of both crops and native vegetation on an estimated 1–2 billion ha of the world's land. Much of this land lies in poor countries whose

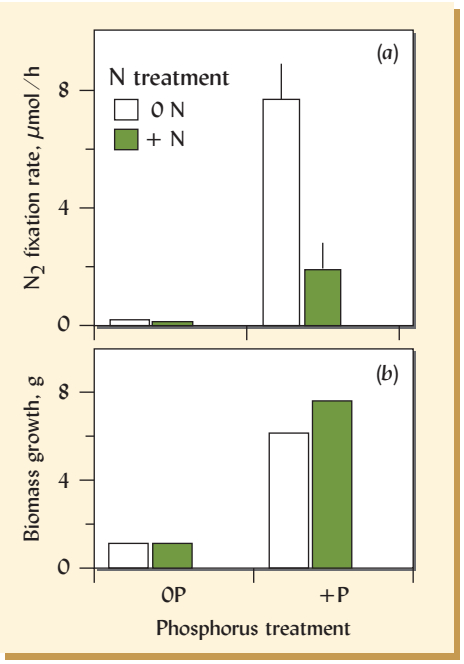

Figure 14.5 *Phosphorus controls symbiotic nitrogen fixation and growth by tropical rainforest tree* Inga punctata. *Biomass was very small and nitrogen fixation almost nonexistent when the trees were grown in phosphorus-poor soil (Typic Eutrudept) from a Panamanian rainforest (0P, left side of each graph). Even though the tree roots exuded phosphatases and were colonized by mycorrhizal fungi (Section 14.9), they were not able to extract sufficient P from the unfertilized soil. When fertilizer P was added, nitrogen fixation and growth were very rapid. Nitrogen fertilizer added with P increased tree biomass, but inhibited symbiotic nitrogen fixation, as explained in Section 13.5.* [Modified from Batterman et al. (2013)]

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farmers have little money for fertilizers. Halting and reversing this type of land degradation will require managing the phosphorus cycle to make efficient use of scarce phosphorus resources.

Water Quality Degradation

Accelerated or cultural eutrophication is caused by phosphorus (and nitrogen) entering streams from both **point sources** and **nonpoint sources** (Figure 14.6). Point sources, such as outflows from sewage treatment plants and industrial factories, are relatively easy to identify, regulate, and clean up. During the past several decades many developed countries have greatly reduced phosphorus loading from point sources. Nonpoint sources, in contrast, are more difficult to identify and control. Nonpoint sources of phosphorus are principally runoff water and eroded sediments from soils scattered throughout an affected watershed. These diffuse sources of phosphorus are now the main cause of eutrophication in many regions (Box 14.1).

Phosphorus Enrichment of Soils. Phosphorus losses from a watershed can be increased by a variety of human activities; timber harvest, poorly managed livestock grazing, and most types of soil tillage make soils more susceptible to erosion and thus loss of phosphorus bound to sediment particles (**particulate-P**). In addition, application of phosphorus-containing animal manures, fertilizers, and even green cover crop residues can increase the concentration of soluble phosphorus near the soil surface, increasing potential losses as P dissolved in runoff water in both inorganic and organic forms (Table 14.1). Because of these effects, soils devoted to agriculture lose far more phosphorus to streams than do those covered by relatively undisturbed grasslands or forests (Figure 14.8).

Animal wastes from industrial-style farms often contain elevated levels of phosphorus because of high levels of phosphorus in animal feeds. Manure is commonly over-applied with respect to the phosphorus needs of crops, especially when it is used as the main source of nitrogen for crops, or when it is applied merely for convenience on fields closest to facilities in

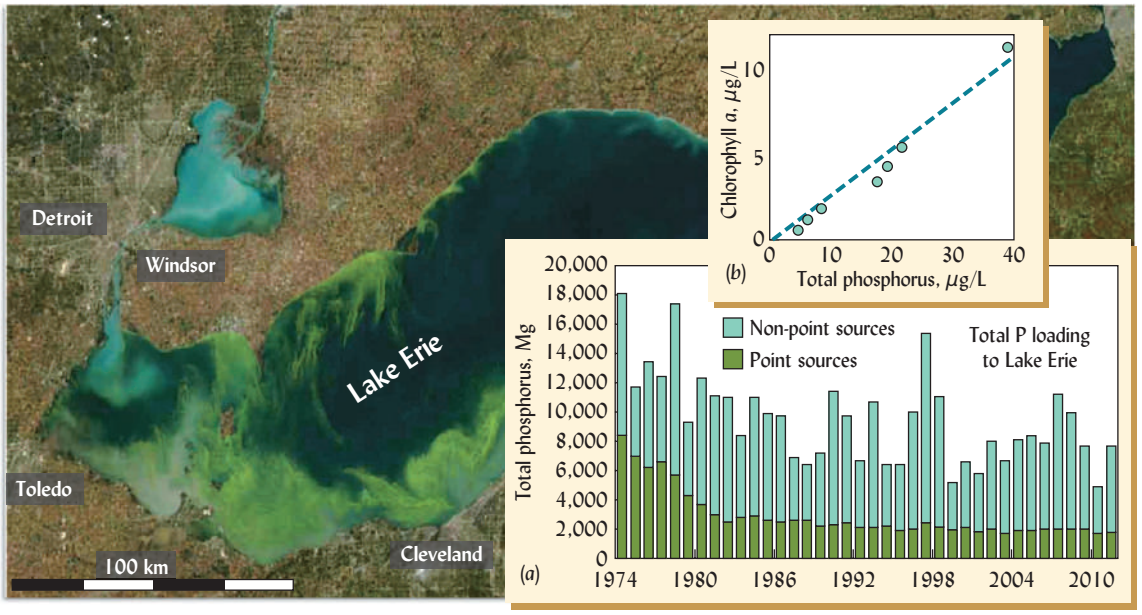

Figure 14.6 *Lake Erie, on the border between the USA and Canada, provides a classic example of phosphorus-driven eutrophication. The satellite image in the background shows an October scene with 1000s of square kilometers of green algal blooms in the eastern portion where rivers draining agricultural and urban areas pour phosphorus into the lake. Graph (a) illustrates how international agreements successfully reduced the point sources during the 1970–1980s, leaving the more difficult to manage nonpoint source derived phosphorus as the main pollution entering the lake. Graph (b) illustrates the relationship between P concentration and chlorophyll (a measure of algal growth) in lake waters.* [Satellite image from NASA; Graph made from data in Ohio Lake Erie Phosphorus Task Force (2013)]

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BOX 14.1

PHOSPHORUS AND EUTROPHICATION

Abundant growth of plants in terrestrial systems is usually considered beneficial, but in aquatic systems too much growth can cause water quality problems. The unwanted growth of algae (floating single-celled plants) and aquatic weeds can make a lake unsuitable as a source of drinking water or as habitat for fish.

In unpolluted lakes and streams, the water is commonly clear, free of excess growth of algae and other aquatic plants, and is inhabited by highly diverse communities of organisms. When phosphorus is added to a phosphorus-limited lake, it stimulates a burst of algal growth (referred to as an *algal bloom*) and, often, a shift in the dominant algal species. The overfertilization is termed **eutrophication**. The word *eutrophication* comes from the Greek *eutruphos*, meaning well-nourished or nourishing. **Natural eutrophication**—the slow accumulation of nutrients over centuries—causes lakes to slowly fill in with dead plants, eventually forming Histosols (see Figure 2.22). Excessive input of nutrients under human influence, called **cultural eutrophication**, tremendously speeds this process. Critical levels of phosphorus in water, above which eutrophication is likely to be triggered, are approximately 0.03 mg/L of dissolved phosphorus and 0.1 mg/L of total phosphorus.

During eutrophication, phosphorus-stimulated algae and plants may suddenly cover the surface of the water with floating plants and turn the water a soupy green algal scum (Figure 14.7). When these aquatic weeds and algae die, they sink to the bottom, where their decomposition by microorganisms uses up the oxygen dissolved in the water. The process is accelerated by warm water temperatures. The decrease in oxygen (anoxic conditions) severely limits the growth of many aquatic organisms, especially fish. Such eutrophic lakes often become turbid, limiting growth of beneficial submerged aquatic vegetation and benthic (bottom-feeding) organisms that serve as food for much of the fish community. In extreme cases eutrophication algal blooms can lead to massive fish kills (Figure 14.7).

Eutrophic conditions favor the growth of *Cyanobacter*, so-called blue-green algae, at the expense of zooplankton, a major food source for fish. These *Cyanobacter* produce toxins and bad-tasting and bad-smelling compounds that make the water unsuitable for human or animal consumption. Some filamentous algae can clog water treatment intake filters and thereby increase the cost of water remediation. Dense growth of both algae and aquatic weeds may make the water useless for boating and swimming. Furthermore, eutrophic waters generally have a reduced level of biological diversity (fewer species) and fewer fish of desirable species. (See also Box 13.3 on eutrophication and nitrogen.) Thus, eutrophication can transform clear, oxygen-rich, good-tasting water into cloudy, greenish, oxygen-poor, foul-smelling, bad-tasting, and possibly toxic water in which a healthy aquatic community cannot survive.

Figure 14.7 *In extreme cases, phosphorus runoff from overfertilized land can result in massive fish kills. Elevated levels of phosphorus in lake and river water can stimulate so much algal growth that the water turns anoxic when the algae die and decompose. The lack of oxygen, in turn, can suffocate aquatic life, including fish.* (Photos courtesy of Ray R. Weil)

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Table 14.1
INORGANIC AND ORGANIC PHOSPHORUS(P) DISSOLVED BY WATER FROM MANURES, COMPOSTS, AND COVER CROPS

The high levels of soluble P in the manures are largely a result of the excessive addition of P to animal feeds. Freeze-killing of cover crops caused plant cells to lyse, releasing P from cells. While much of the dissolved P may react with the soil, some will flow with surface runoff or follow preferential channels to groundwater.

	P dissolved by simulated rain water, mg P/kg dry matter	
Manure/Compost/Crop residue	**Inorganic P**	**Organic P**
Dairy manure	1925	375
Dairy compost	2232	232
Poultry manure	4380	1531
Poultry litter	2918	400
Poultry compost	1859	53
Swine slurry	3994	972
Oilseed radish, not frozen	6	5
Oilseed radish, freeze-killed	320	20
Perennial ryegrass, not frozen	13	7
Perennial ryegrass freeze-killed	182	58

Data for manure and compost from Sharpley and Moyer (2000) and for crop residues from Liu et al. (2013).

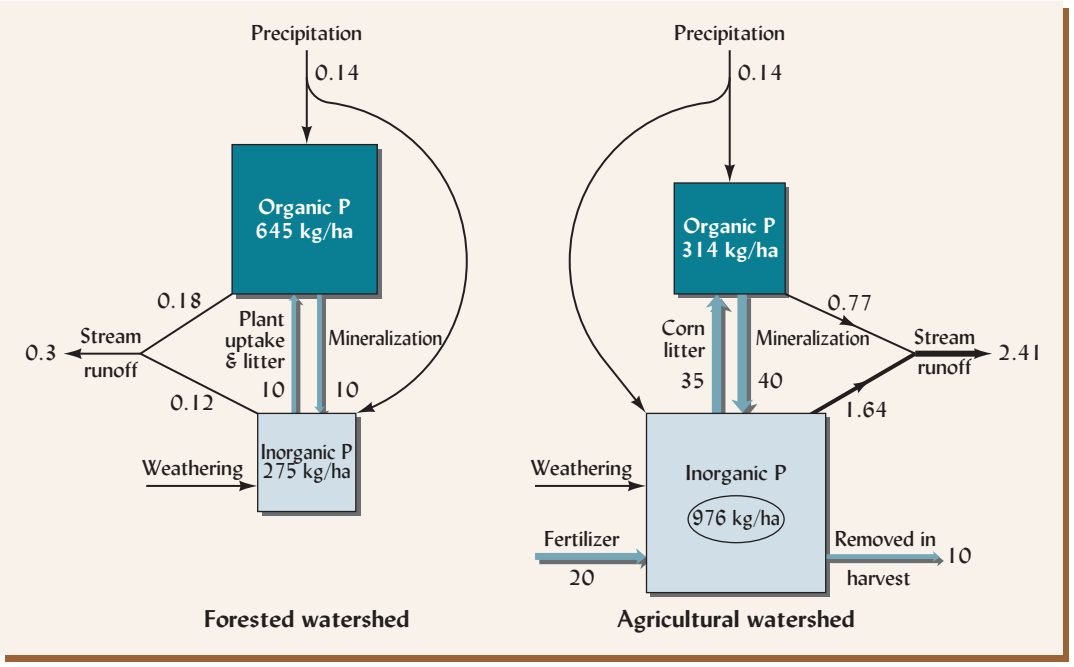

Figure 14.8 *Phosphorus balance in surface soils (Ultisols) of adjacent forested and agricultural watersheds. The forest consisted primarily of mature hardwoods that had remained relatively undisturbed for 45 or more years. The agricultural land was producing row crops for more than 100 years. It appears that in the agricultural soil, about half of the organic phosphorus has been converted into inorganic forms or lost from the system since cultivation began. At the same time, substantial amounts of inorganic phosphorus accumulated from fertilizer inputs. Compared to the forested soil, mineralization of organic phosphorus was about four times as great in the agricultural soil, and the amount of phosphorus lost to the stream was eight times as great. Flows of phosphorus, represented by arrows, are given as kg/ha/yr. Although not shown in the diagram, it is interesting to note that nearly all (95%) of the phosphorus lost from the agricultural soil was in particulate form, while losses from the forest soil were 33% dissolved and 77% particulate.* [Based on data from Vaithiyanathan and Correll (1992)]

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which livestock are confined. Runoff and erosion from resulting P-saturated soils contribute to serious downstream eutrophication problems. On some low-lying soils with artificial drainage systems, phosphorus losses by leaching can also be significant.

Phosphorus Losses in Runoff. Agricultural management that involves disturbing the soil surface with tillage generally increases the amount of phosphorus carried away on eroded sediment (i.e., particulate P). On the other hand, fertilizer, manure, or even high-phosphorus content crop residue left unincorporated on the surface of cropland or pastures usually leads to increased losses of phosphorus dissolved in the runoff water (i.e., **dissolved P**). These trends can be seen in Table 14.2 by comparing phosphorus losses from no-till and conventionally tilled wheat fields.

The decision to use tillage to incorporate phosphorus-bearing soil amendments involves a trade-off between the advantages of incorporating phosphorus into the soil (less phosphorus dissolves in the runoff water and more is available for plant uptake) and the disadvantages associated with disturbing the surface soil (increased loss of soil particles by erosion and usually increased amounts of runoff water; see Table 14.2). In no-tillage systems, surface application of manure without incorporation may result in lower total loss of phosphorus, because this type of management achieves substantial reductions in soil erosion and total runoff. The effect of these reductions may or may not outweigh the effect of the increased phosphorus concentration in the relatively small volume of water that does run off. If the equipment is available to do so, the best option might be to handle the high-phosphorus amendment as a liquid and inject it into the soil with a minimum of disturbance to the soil surface (Section 16.4). Equipment has been developed that can also inject solid poultry manure if it has been dried and pelleted to make it "flowable."

Disturbances to natural vegetation, such as timber harvest or wildfires, also increase the loss of phosphorus. Fires tend to release soluble phosphorus from organic matter and litter, making it susceptible to loss in runoff (Figure 14.9). Other disturbances primarily increase phosphorus loss via sediment. Erosion predominantly transports the clay and organic matter fractions of the soil (which are relatively rich in phosphorus), leaving behind the coarser, lower-phosphorus fractions. Thus, compared to the original soil, eroded sediment

Table 14.2
INFLUENCE OF WHEAT PRODUCTION AND TILLAGE ON ANNUAL LOSSES OF PHOSPHORUS(P) IN RUNOFF WATER AND ERODED SEDIMENTS COMING FROM SOILS IN THE SOUTHERN GREAT PLAINS
The total P lost includes the P dissolved in the runoff water and the P adsorbed to the eroded particles.[a] *Although cattle grazing on the natural grasslands probably increased losses of P from these watersheds, the losses from the agricultural watersheds were about ten times as great. The no-till wheat fields lost much less particulate P, but more dissolved P, than did the conventionally tilled wheat fields.*

		kg P/ha/yr		
Location and soil	Management	Dissolved P	Particulate P	Total P
El Reno, Oklahoma Paleustolls, 3% slope	Wheat with conventional plow and disk	0.21	3.51	3.72
	Wheat with no-till	1.04	0.43	1.42
	Native grass, heavily grazed	0.14	0.10	0.24
Woodward, Oklahoma Ustochrepts, 8% slope	Wheat with conventional sweep plow and disk	0.23	5.44	5.67
	Wheat with no-till	0.49	0.70	1.19
	Native grass, moderately grazed	0.02	0.07	0.09

[a]Wheat was fertilized with up to 23 kg/ha of P each fall.
Data from Smith et al. (1991).

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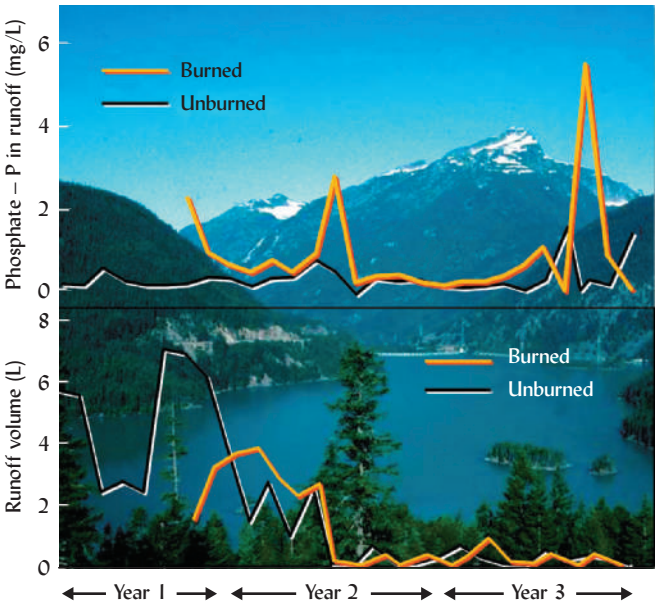

Figure 14.9 *Effect of wildfires on nutrient runoff in the Sierra Nevada Mountains surrounding Lake Tahoe in the United States. The renowned clarity of Lake Tahoe's waters has suffered in recent years, and research suggests that runoff of P (as well as N) from the mountain slopes is partly responsible for the eutrophication of the lake. Note that although the wildfire had little effect on the runoff volumes generated, the runoff from burned areas sporadically contained much more reactive phosphate-P (PO_4–-P), even several years after the fire.* [Graphed from data in Miller et al. (2006); Photo courtesy of Ray R. Weil]

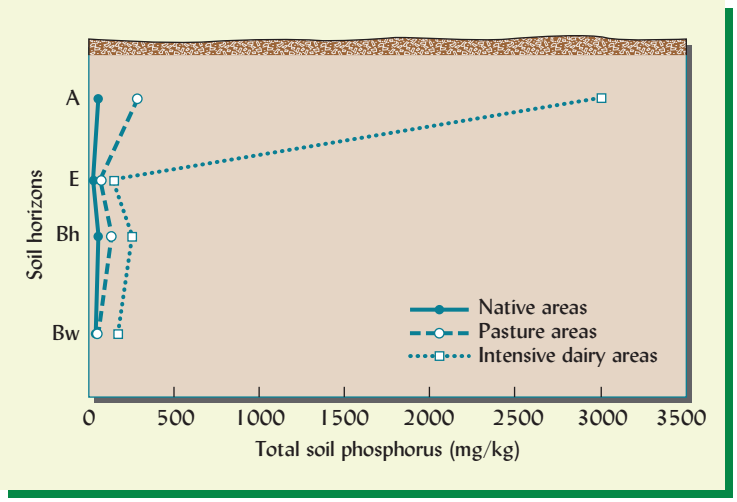

Figure 14.10 *Average total soil phosphorus levels of intensively used areas, and nearby pasture and native (forested) areas of three dairy farms near Lake Okeechobee in South Florida, USA. The intensively used areas near the barns where cattle are held prior to milking are extremely high in phosphorus, some of this element having moved down into the subsoil of these sandy Spodosols. Runoff water from such areas of animal concentration is a major source of phosphorus that stimulates eutrophication in streams and lakes.* [Drawn from data in Nair et al. (1995)]

often has more than twice the concentration of phosphorus—an **enrichment ratio** of 2 or more being typical.

Livestock Concentration. Runoff from facilities where thousands of cattle, hogs, or poultry are confined is an increasingly significant source of phosphorus that contributes to eutrophication. Manure from 10,000 beef cattle contains as much phosphorus and nitrogen as is found in human wastes from a city of 100,000 (see Section 16.4). Phosphorus may be washed off the manure-laden livestock holding areas, or off the nearby fields which are conveniently located for repeated manure applications and commonly accumulate very large concentrations of phosphorus near the soil surface (Figure 14.10).

14.3 THE PHOSPHORUS CYCLE

If we are to successfully manage phosphorus for economic plant production, for ecosystem services, and for environmental protection, we need to understand the nature of the different forms of phosphorus found in soils and the manner in which these forms of phosphorus

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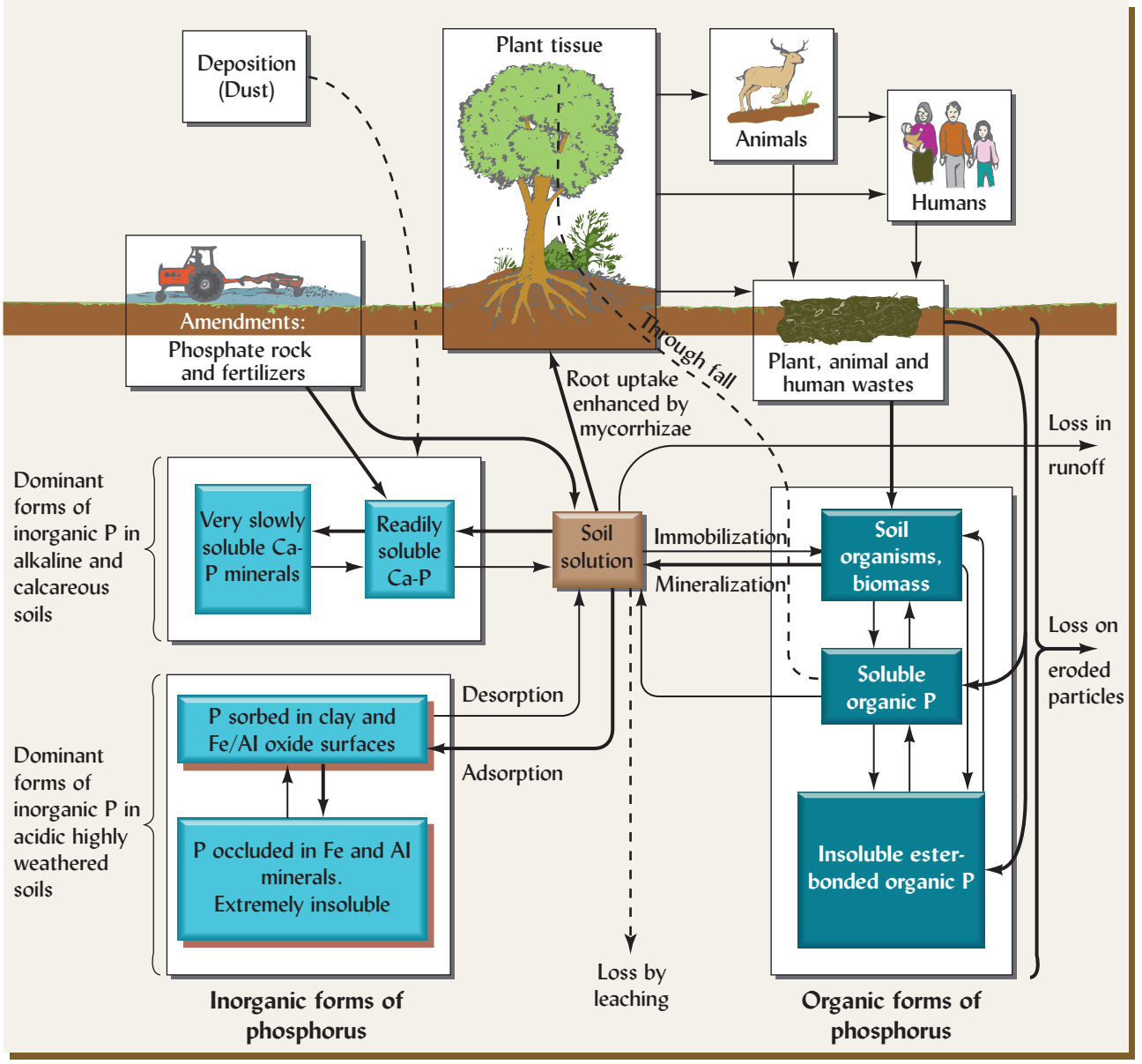

Figure 14.11 *The phosphorus cycle in soils. The boxes represent pools of the various forms of phosphorus in the cycle, while the arrows represent translocations and transformations among these pools. The three largest white boxes indicate the principal groups of phosphorus-containing compounds found in soils. Within each of these groups, the less soluble, less available forms tend to dominate. Thick arrows represent the principal pathways.* (Diagram courtesy of Ray R. Weil)

interact with the soil and the larger environment. The cycling of phosphorus within the soil, from the soil to plants and back to the soil, is illustrated in Figure 14.11.

Phosphorus in Soil Solution. Compared to other macronutrients, such as nitrogen, sulfur, or calcium, the concentration of phosphorus in the soil solution is very low, generally ranging from 0.001 mg/L in very infertile soils to about 1 mg/L in rich, heavily fertilized soils. Plant roots absorb phosphorus dissolved in the soil solution using a cross-membrane transporter specific for phosphate ions (HPO_4^{2-} and $H_2PO_4^-$), but some soluble organic phosphorus compounds may also be taken up. The chemical species of phosphate ions present is determined by the solution pH (Figure 14.12). In strongly acid soils (pH 4–5.5), the monovalent anion $H_2PO_4^-$ dominates, while alkaline solutions are characterized by the

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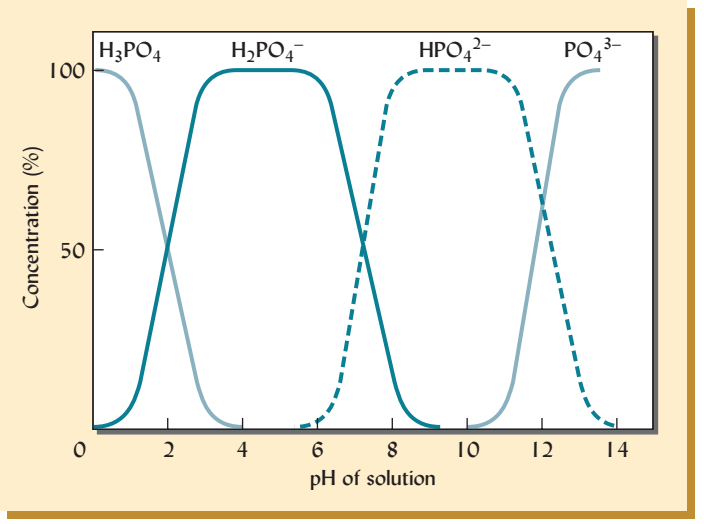

Figure 14.12 *The effect of pH on the relative concentrations of the species of phosphate ions. At lower pH values, more H^+ ions are available in the solution, and thus the phosphate ion species containing more hydrogen predominates. In near-neutral soils, HPO_4^{2-} and $H_2PO_4^-$ are found in nearly equal amounts. Both of these species are readily available for plant uptake.*

divalent anion HPO_4^{2-}. Both anions are important in near-neutral soils. Of the two anions, $H_2PO_4^-$ is thought to be slightly more easily taken up by plants, but effects of pH on phosphorus reactions with other soil constituents are more important than the particular phosphorus anion present.

Not only are phosphate ions in low supply in the soil solution, they are also quite immobile because they react strongly with components on the surfaces of soil particles. Therefore phosphate ions are very slow to move downward through the soil matrix with percolating water and leaching losses are generally quite small (except in cases where clay particles carrying sorbed P are dispersed in the leaching water).

The phosphate ions are also very slow to move toward the root by diffusion. Slow diffusion to root surfaces curtails the root uptake of phosphorus (as well as of such other nutrients as Zn and K). As plants take up phosphorus from the root zone faster than it can diffuse in, a **depletion zone** is created with greatly reduced phosphorus concentration in the soil solution adjacent to roots and root hairs (Figure 14.13, *left*). The depletion zone around a root is smaller but more pronounced when soil physical factors, such as dryness, compaction, or cold temperatures, limit the diffusion rate of phosphate ions through the soil solution. Plant roots therefore generally find themselves growing in a soil solution depleted in phosphorus compared to the bulk soil. To compensate, roots must continually extend into and proliferate in new soil zones not yet depleted.

Uptake by Roots and Mycorrhizae.[5] Fortunately, for most plants, the roots are not alone in their struggle to obtain sufficient phosphorus from soils—they are aided by a symbiotic

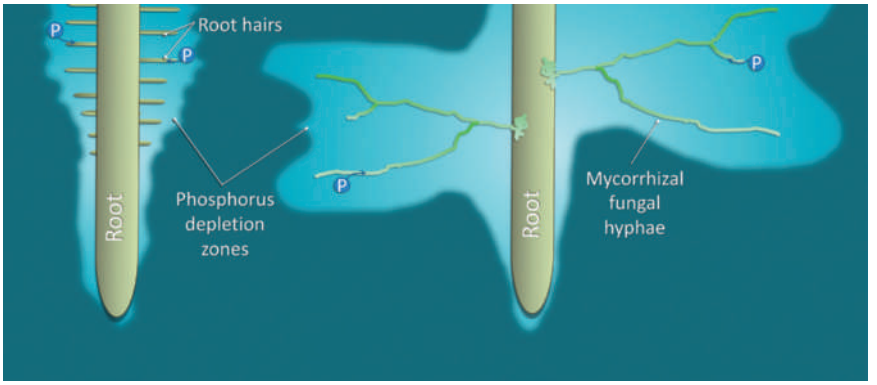

Figure 14.13 *Mycorrhizal root colonization enlarges the volume of soil (the depletion zone) where phosphate ions are taken up faster than they can diffuse in from nearby zones of higher concentration. Mycorrhizal roots may obtain P by both root hair uptake and hyphal uptake, but in some cases the fungi inactivate root P uptake mechanisms.* (Diagram courtesy of Ray R. Weil)

[5]For a review of advances in our knowledge of the complex plant–fungal interaction affecting phosphorus nutrition, see Smith et al. (2011).

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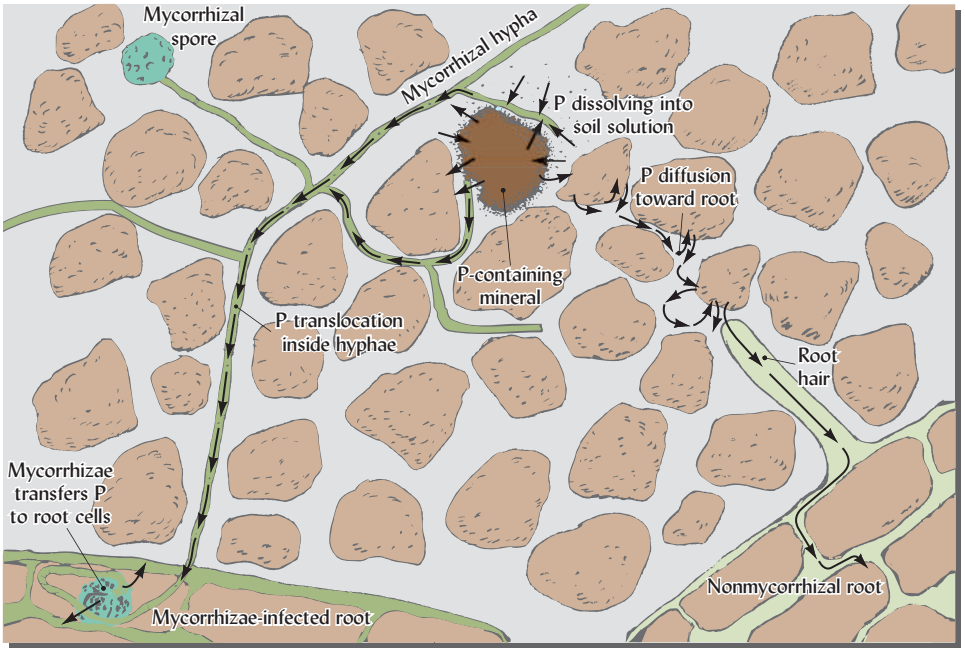

Figure 14.14 *Roles of diffusion and mycorrhizal hyphae in the movement of phosphate ions to plant roots. In soils with low solution phosphorus concentration and high phosphorus fixation, slow diffusion may seriously limit the ability of roots to obtain sufficient phosphorus. The hyphae of symbiotic mycorrhizal fungi help overcome this problem. They penetrate the soil, absorb the phosphorus, and by cytoplasmic streaming inside the hyphae, transport phosphorus to the plant roots. This makes a plant much less dependent on the diffusion of phosphate ions through the soil.* (Diagram courtesy of Ray R. Weil)

partnership with mycorrhizal fungi (see also Section 11.9, Figures 11.33 and 11.34). The microscopic, threadlike mycorrhizal hyphae colonize root cortical cells and extend out into the soil several centimeters from the root surface, exploiting phosphorous from a much larger volume of soil than could the roots by itself (Figure 14.13, *right*). The hyphae are effective in absorbing phosphate ions as they enter the soil solution and may even be able to access some strongly bound forms of phosphorus. The fungi then translocate the phosphate ions inside their hyphal cells, where soil-retention mechanisms cannot interfere with phosphate movement (Figure 14.14).

This mycorrhizal association is generally best developed where host plants are growing in undisturbed soils with low phosphorus availability. However, the fungi have been observed to benefit early-season growth of annual plants even in soils testing high in available phosphorus if the soil is kept vegetated with plants that can serve as suitable hosts (e.g., Table 14.3). Colonization by AM fungi usually, but not always, enhances total phosphorus uptake and plant growth. The plant "pays" the fungi for this service by sharing 5–20% of its photosynthate production.

Decomposition of Plant Residues. Once in the plant root, a portion of the phosphorus is translocated to sites where it is incorporated into plant tissues. As the plants shed leaves and their roots die, or when they are eaten by animals (including people), phosphorus returns to the soil in the form of plant residues, leaf litter, and animal wastes.

Microorganisms that decompose the residues temporarily tie up at least part of the phosphorus in their cells (microbial biomass-P), but eventually release phosphorus to the soil solution through mineralization (Section 12.2). Some of the plant and microbial organic phosphorus becomes part of the labile and more stable, protected pools of soil organic matter (see Section 12.6). These organic matter pools mineralize at various rates, releasing soluble forms of phosphorus that plant roots can absorb, thereby repeating the cycle.

Chemical Forms in Soils. In most soils, the amount of phosphorus available to plants from the soil solution at any one time is very low, seldom exceeding about 0.01% of the total phosphorus in the soil. The bulk of the soil phosphorus exists in three general groups of compounds—namely, *organic phosphorus*, *calcium-bound inorganic phosphorus*, and *iron- or aluminum-bound inorganic phosphorus* (see Figure 14.11). The organic phosphorus is distributed among the biomass, *labile* and *protected* or *passive* fractions of soil organic matter

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Table 14.3
PREVIOUS LAND USE (FALLOW VS. CROP) AFFECTS EARLY SEASON MYCORRHIZAL COLONIZATION, AND CORN CHARACTERISTICS ON A SOIL TESTING HIGH IN AVAILABLE PHOSPHORUS
Lack of a continuous host for mycorrhizal fungi due to previous fallow resulted in reduced corn root colonization at the three-leaf stage. This depressed growth and P uptake by the six-leaf stage and led to lower grain yields. Practices that encourage mycorrhizae may help plants take off quickly without starter fertilizer.

	Previous land use	Mycorrhizal root colonization on 3-leaf stage corn, %	Shoot dry wt. at 6-leaf stage, kg/ha	P concentration at 6-leaf stage, %	P uptake at 6-leaf stage, g/ha	Grain yield, kg/ha
Year 1	Host crop	20.2	193	0.284	563	2903
	Fallow	11.0	142	0.228	337	2378
Year 2	Host crop	46.9	103	0.262	273	7176
	Fallow	12.8	81	0.178	148	6677
Year 3	Host crop	17.2	261	0.336	882	5495
	Fallow	8.0	158	0.293	469	4980

Data selected from Bittman et al. (2006).

(see Section 12.6). Of the inorganic phosphorus, the calcium compounds predominate in most alkaline soils, while the iron and aluminum forms are most important in acidic soils. All three groups of compounds slowly contribute phosphorus to the soil solution, but most of the phosphorus in each group is of very low solubility and not readily available for plant uptake.

Unlike nitrogen and sulfur, phosphorus is not generally lost from the soil in gaseous form (but small amounts may be lost as fishy-smelling phosphine gas (PH_3)—a phenomenon noted in certain graveyard soils). Because soluble inorganic forms of phosphorus are strongly adsorbed by mineral surfaces (see Section 14.6), leaching losses of inorganic phosphorus are generally very low, but they still may be sufficient under certain circumstances to stimulate eutrophication in downstream waters.

Gains and Losses. The principal pathways by which phosphorus is lost from the soil system are plant removal (5–50 kg ha^{-1} yr^{-1}), erosion of phosphorus-carrying soil particles (0.1–10 kg ha^{-1} yr^{-1} on organic and mineral particles), phosphorus dissolved in surface runoff water (0.01–3.0 kg ha^{-1} yr^{-1}), and leaching to groundwater (0.0001–0.5 kg ha^{-1} yr^{-1}). For each pathway, the higher figures cited for annual phosphorus loss would most likely apply to cultivated soils (see Section 16.12 and Figure 14.8). The amount of phosphorus that enters the soil from the atmosphere (sorbed on dust particles) is quite small (0.05–0.5 kg ha^{-1} yr^{-1}), but may nearly balance the losses from the soil under natural vegetation.

As already discussed, in agroecosystems on low phosphorus soils, optimal crop production may initially require the input from fertilizer to exceed the removal in crop harvest. However, this level of phosphorus input can be justified only until enough phosphorus accumulates to reduce the P-fixing capacity of the soil (see Section 14.8). The level of soil fertility and severity of environmental P pollution generated by farmland are largely determined by the balance—or lack of balance—between P imports to a farm in fertilizer and feed and exports in plant and animal products. Figure 14.15 illustrates that urban ecosystems are characterized by more complex budgets of phosphorus imports and exports, but are also likely to get out of balance such that phosphorus resources are wasted and streams and lakes become polluted.

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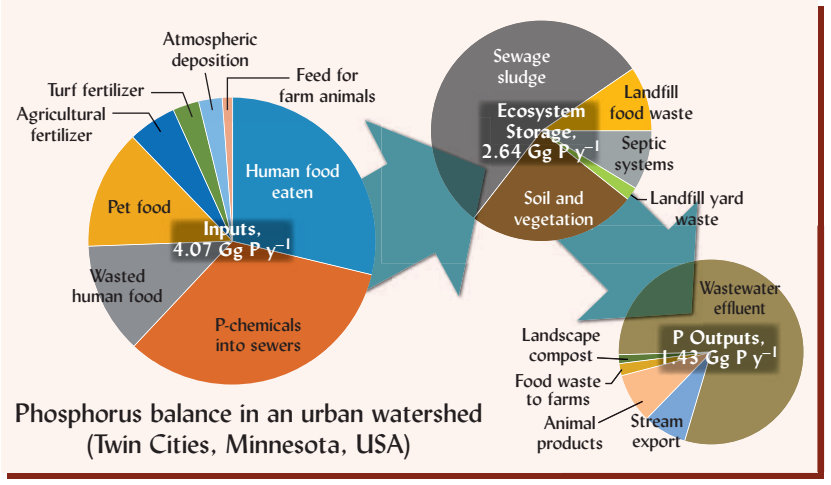

Figure 14.15 *The phosphorus balance for the 3011 km² watershed that includes Minneapolis and St. Paul Minnesota, USA with 2.1 million people and about a million pet cats and dogs. About 9% of the land was still in agricultural use. Most of the 4.07 Gg (4070 metric tons) of P entering the watershed was in food and chemicals (e.g. detergents, etc.); most of the 1.41 Gg of P that left the watershed was unintentional loss in wastewater and runoff to steams. Some 2.64 Gg of P was stored in the watershed as landfilled waste or P-enriched soils. Clearly, cities should be able to find many opportunities to improve efficiency of use and recycling of phosphorus resources.*
[Graphed from data in Baker et al. (2011)]

14.4 ORGANIC PHOSPHORUS IN SOILS[6]

Plants use phosphorus from both inorganic and organic soil components. The organic fraction generally constitutes 20–80% of the total phosphorus in surface soil horizons (Table 14.4). The deeper horizons may hold large amounts of inorganic phosphorus, especially in soils from arid and semiarid regions (Figure 14.16).

Organic Phosphorus Compounds

For many decades, scientists focused most of their attention on the inorganic rather than on the organic phosphorus in soils, and our knowledge of the specific nature of much of the organic-bound phosphorus in soils is quite limited. Modern spectrographic methods are revealing more detail about the organic P in soils. The bulk of soil organic P appears to occur as mono- and di-esters, in which P atoms are bonded to carbons indirectly via oxygens (Figure 14.17). Three broad groups of organic phosphorus compounds are quite common in soils: (1) inositol phosphates or phosphate mono-esters of a sugarlike compound, inositol [$C_6H_6(OH)_6$]; (2) phosphate di-esters such as nucleic acids from DNA and RNA; and (3) phospholipids, partially derived from microbial and plant cell membranes. While other organic phosphorus compounds are present in soils, their identities are less well understood and the amounts present are quite small.

Inositol phosphates are the most abundant of the known organic phosphorus compounds, making up 10–60% of the total organic phosphorus. Their abundance in soils is probably related to their high stability in both acid and alkaline conditions, and their high charge density which facilitates interaction with soil humus and mineral surfaces. One of the most common inositol phosphates in soils is *phytic acid*, a compound in which plants store P in their seeds (including grains like corn). The fact that nonruminant animals cannot digest phytic acid means that grain-fed swine and poultry require supplemental phosphorus in their feed and that their manure may be artificially high in phosphorus (see Section 16.4).

Nucleic acids are adsorbed by both organic and mineral soil colloids, helping to protect the phosphorus in nucleic acids from microbial attack. Still, the nucleic acids and phospholipids together probably make up only 1–2% of the organic phosphorus in most soils.

The other chemical compounds that contain most of the soil organic phosphorus have not yet been identified. Our ignorance of the specific compounds involved does not detract from the importance of these compounds as suppliers of phosphorus through microbial breakdown.

[6]For a review of organic P and its management in agricultural soil systems, see Dodd and Sharpley (2015).

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Table 14.4
TOTAL PHOSPHORUS CONTENT OF SURFACE SOILS FROM DIFFERENT LOCATIONS AND THE PERCENTAGE OF TOTAL PHOSPHORUS IN THE ORGANIC FORM

Soils	Number of samples	Total P, mg/kg	Organic fraction, %
New York, USA			
Histosols (cultivated)	8	1491	52
Iowa, USA			
Mollisols and Alfisols	6	561	44
Maryland, USA			
Ultisols (silt loams)	6	650	59
Ultisols (forested sandy loams)	3	472	70
Ultisols (sandy loam, cropland)	4	647	25
Arizona, USA	19	703	36
Australia	3	422	75
Texas, USA			
Ustolls	2	369	34
Hawaii, USA			
Andisol	1	4700	37
Oxisol	1	1414	19
Ethiopia highlands			
Vertisols	15	454	47
Zimbabwe			
Alfisols	22	899	56

Data for Iowa and Arizona from sources quoted by Brady (1974); Australia from Fares et al. (1974); New York from Cogger and Duxbury (1984); Hawaii from Soltanpour et al. (1988); Zimbabwe from Ray R. Weil and F. Folle, unpublished; Texas from Raven and Hossner (1993); Maryland (silt loams) from Weil et al. (1988); Maryland (sandy loams) from Vaithiyanathan and Correll (1992); Ethiopian Vertisols from Tekalign et al. (1988).

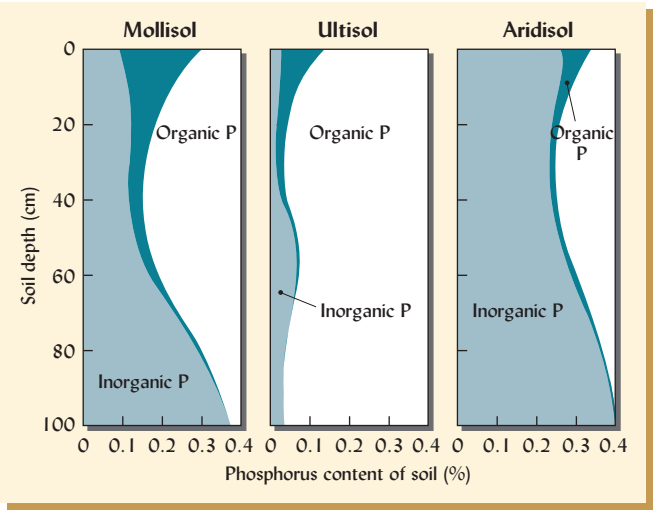

Figure 14.16 *Phosphorus contents of representative soil profiles from three soil orders. All three soils contain a relatively high proportion of organic phosphorus in their surface horizons. The Aridisol has a high inorganic phosphorus content throughout the profile because rainfall during soil formation was insufficient to leach much of the inorganic phosphorus compounds from the soil. The increased phosphorus in the subsoil of the Ultisol is due to adsorption of inorganic phosphorus by iron and aluminum oxides in the B horizon. In both the Mollisol and Aridisol, most of the subsoil phosphorus is in the form of inorganic calcium-phosphate compounds.* (Diagram courtesy of Ray R. Weil and N. Brady)

Traditional colorimetric methods (e.g., molybdenum blue) measure only inorganic orthophosphate forms of dissolved phosphorus. However, recent research suggests that 50% or more of the water-soluble phosphorus in the soil solution and in leachates or runoff water from soils is present as **organic phosphorus** compounds (Figure 14.18). This is especially true where livestock have been grazed or manure has been applied. Dissolved organic phosphorus (DOP) is generally more mobile than soluble inorganic phosphates, probably because it is not

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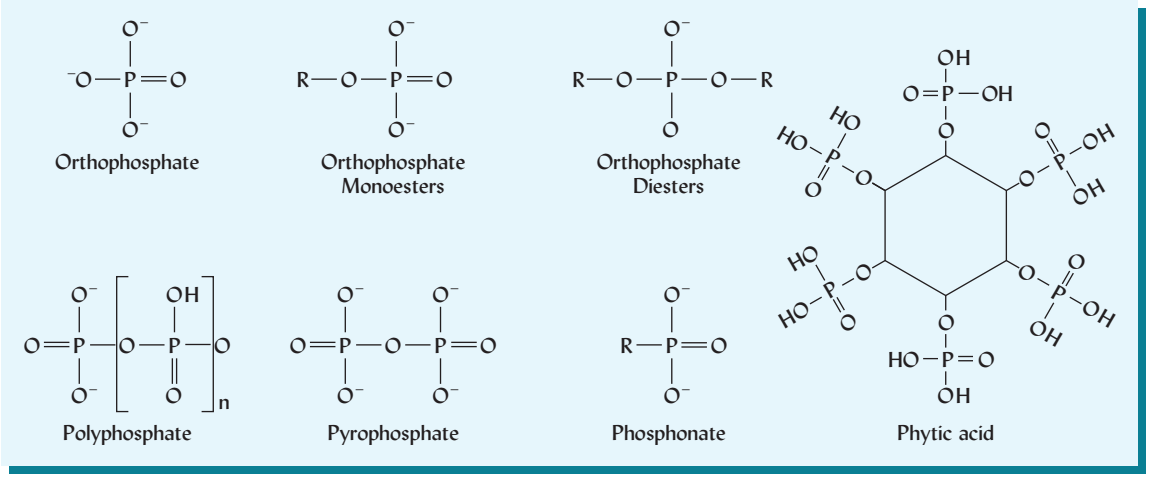

Figure 14.17 *Types of organic phosphorus compounds commonly found in soils, where "R" stands for the rest of a larger organic molecule. Most organic soil phosphorus occurs as some form of phosphate ester. The inorganic orthophosphate ion is also represented (far left, upper). Phytic acid (far right), a plant storage molecule and example of a phosphate mono-ester, is one of the most plentiful organic phosphorus compounds in soils. The nucleic acids that comprise the genetic coding molecule, DNA, are examples of a phosphate di-esters common in small amounts in soils.* (Diagram courtesy of Ray R. Weil)

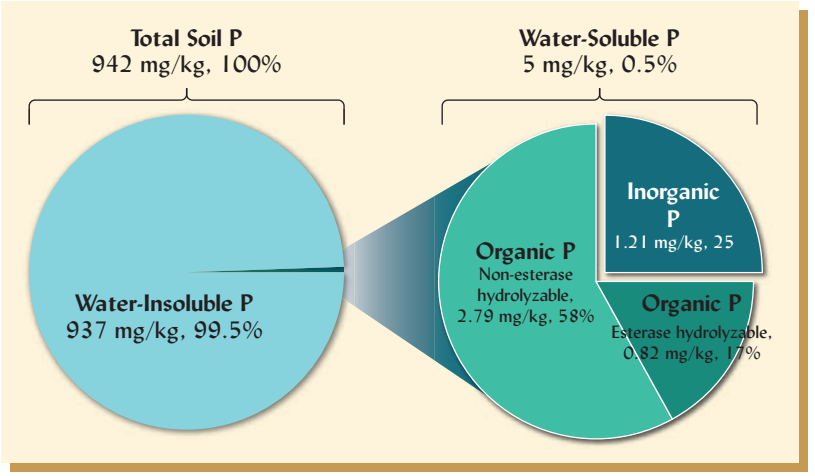

Figure 14.18 *Forms of water-soluble phosphorus in slightly acid sandy loam and silt loam surface soils under unfertilized pastures.* (Left) *Of a total concentration of 942 mg P per kg soil (dry mass basis), only 0.5% (5 mg/kg) was water soluble (extractable by shaking dried soils in distilled water).* (Right) *Of the water-soluble P, only 17% (dark blue slice) was inorganic phosphate measurable by traditional colorimetric chemistry. The remainder was organic, about ¼ of which was hydrolysable by phosphate esterase enzymes and therefore could be used by algae in waterways. To accurately predict how soluble phosphorus may influence eutrophication and plant nutrition both organic and inorganic P must be measured.* [Diagram courtesy of Ray R. Weil using means for 14 alluvial Vermont Inceptisols in Young et al. (2013)]

so readily adsorbed by organic matter, clays, Fe/Al oxide, and calcium carbonate in the soil. As a consequence, in heavily manured areas with sandy soils DOP can leach downward to nearly 2 m (Figure 14.19). In fields with high water tables, the phosphorus can move with the groundwater to nearby drainage ditches, streams, and lakes where it may contribute significantly to eutrophication.

Mineralization of Organic P

Phosphorus held in organic forms can be mineralized and immobilized by the same general processes that release nitrogen and sulfur from soil organic matter (see Chapter 13):

$$\text{Organic P forms} \underset{\text{Microbes}}{\overset{\text{Microbes}}{\rightleftharpoons}} \underset{\text{Soluble phosphate}}{H_2PO_4^-} \underset{\longrightarrow\ \text{Mineralization}\ \longrightarrow}{\overset{\longleftarrow\ \text{Immobilization}\ \longleftarrow}{\overset{Fe^{3+},\ Al^{3+},\ Ca^{2+}}{\rightleftharpoons}}} \underset{\text{Insoluble fixed P}}{\text{Fe, Al, Ca phosphates}} \qquad (14.1)$$

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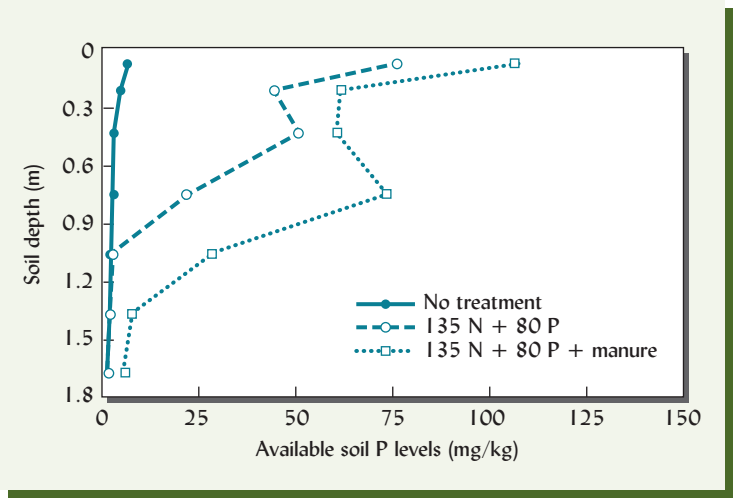

Figure 14.19 *Effect of adding fertilizer with and without cow manure for a period of 42 years on the available phosphorus at different soil depths where corn had been grown every year. The soil was a Tripp very fine sandy loam (Typic Haplustolls) with alkaline (pH 8.3) and calcareous subsoil layers. Both treatments resulted in large available P in the upper horizons, but only where manure was also applied did increases appear below a depth of 1 m. Apparently the organic forms of P in the manured plot were not adsorbed by the soil, thereby permitting deeper penetration of the phosphorus, which may then have been subject to movement through the groundwater to nearby waterways.* [Drawn from selected data in Eghball et al. (1996)]

Net immobilization of soluble phosphorus is most likely to occur if residues added to the soil have a C/P ratio greater than 300:1, while net mineralization is likely if the ratio is below 200:1. Mineralization of organic phosphorus in soils is subject to many of the same influences that control the general decomposition of soil organic matter—such as temperature, moisture, and tillage (see Section 12.3). In temperate regions, mineralization of organic phosphorus in soils typically releases 5–20 kg P/ha annually, most of which is readily absorbed by growing plants. These values can be compared to the annual uptake of phosphorus by most crops, trees, and grasses, which generally ranges from 5 to 30 kg P/ha.

When forested soils are first brought under cultivation in tropical climates, the amount of phosphorus annually released by mineralization may exceed 50 kg/ha, but unless phosphorus is added from outside sources these high rates of mineralization will soon decline due to the depletion of readily decomposable soil organic matter. In Florida, USA, rapid mineralization of organic matter in Histosols (Saprists) drained for agricultural use is estimated to release about 80 kg P/ha/yr. Unlike most mineral soils, these organic soils possess little capacity to retain dissolved phosphorus, so water draining from them is quite concentrated in phosphorus (0.5–1.5 mg P/L) and is thought to be contributing to the degradation of the Everglades wetland system in the United States.

Contribution of Organic Phosphorus to Plant Needs

Although it used to be thought that plant roots could take up only inorganic ions, it is now known that many plants are also able to directly absorb some small organic phosphorus (and nitrogen) containing molecules. Although, the level of such absorption is thought to be very low compared to that of inorganic phosphates in fertilized agricultural soils, this is difficult to determine because the chemistry used to measure phosphate can readily hydrolyze small soluble organic molecules and release inorganic phosphate in the process.

Regardless of whether direct plant uptake of organic phosphorus plays an important role or not, the readily decomposable or easily soluble fractions of soil *organic phosphorus* are often the most important factor in supplying phosphorus to plants in *highly weathered soils* (e.g., Ultisols and Oxisols), even though the total organic matter content of these soils may not be especially high. The inorganic phosphorus in the highly weathered soils is far too insoluble to contribute much to plant nutrition. Apparently plant roots and mycorrhizal hyphae are able to obtain phosphate released from organic molecules before it forms inorganic compounds that quickly become insoluble. In contrast, it appears that the more soluble *inorganic forms* of phosphorus play the biggest role in the phosphorus fertility of *less weathered soils* (e.g., Mollisols and Vertisols), even though these soils generally contain relatively high amounts of soil organic matter.

Green manure crops and cover crop residues left on the soil surface as a mulch can improve phosphorus availability in both groups of soils. In temperate regions, freezing and thawing can lyse cells in growing plants and fresh residues, rapidly releasing soluble P from the cell cytoplasm (Table 14.1). Under certain soil and weather conditions, some of this soluble organic P may be lost in winter runoff water before the spring flush of plant growth can take it up.

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14.5 INORGANIC PHOSPHORUS IN SOILS

Of all the macronutrients found in soils, phosphorus has by far the smallest quantities in solution or in readily soluble forms in mineral soils. In addition, inorganic phosphorus in mineral soils is notoriously immobile. Two phenomena tend to control the concentration of phosphorus in the soil solution and the movement of phosphorus in soils: (1) the solubility of phosphorus-containing minerals, and (2) the adsorption or fixation of phosphate ions on the surface of soil particles. In practice, it is difficult to separate the influence of these two types of reactions or even determine the exact nature of inorganic phosphorus compounds present in a particular soil.

Fixation and Retention. Dissolved phosphate ions in mineral soils are subject to many types of reactions that tend to remove the ions from the soil solution and produce phosphorus-containing compounds of very low solubility. These reactions are sometimes collectively referred to by the general terms *phosphorus fixation* and *phosphorus retention. Phosphorus retention* is a somewhat more general term that includes both precipitation and fixation reactions.

The tendency for soils to fix phosphorus in relatively insoluble, unavailable forms has far-reaching consequences for phosphorus management. For example, phosphorus fixation may be viewed as troublesome if it prevents plants from using all but a small fraction of fertilizer phosphorus applied. On the other hand, phosphorus fixation can be viewed as a benefit if it causes most of the dissolved phosphorus to be removed from phosphorus-rich wastewater applied to a soil (Box 14.2). The fixation reactions responsible in both situations will be discussed as they apply to the solubility of phosphorus under acidic and alkaline soil conditions. We will begin by describing the various inorganic compounds and their solubility.

Inorganic Phosphorus Compounds

As indicated by Figure 14.11, most inorganic phosphorus compounds in soils fall into one of two groups: (1) those containing calcium, and (2) those containing iron and aluminum (and, less frequently, manganese).

As a group, the calcium phosphate compounds become more soluble as soil pH decreases; hence, they tend to dissolve and disappear from acid soils. On the other hand, the calcium phosphates are quite stable and very insoluble at higher pH and so become the dominant forms of inorganic phosphorus present in neutral to alkaline soils.

Of the common calcium compounds containing phosphorus (Table 14.5), the **apatite** minerals are the least soluble and are therefore the least plant-available source of phosphorus. Some apatite minerals (e.g., fluorapatite) are so insoluble that they persist even in weathered (acid) soils. The simpler mono- and dicalcium phosphates are readily available for plant uptake. Except on recently fertilized soils, however, these compounds are present in only extremely small quantities because they easily revert to the more insoluble forms.

In contrast to calcium phosphates, the iron and aluminum hydroxy phosphate minerals, **strengite** ($FePO_4 \cdot 2H_2O$) and **variscite** ($AlPO_4 \cdot 2H_2O$), have very low solubility in strongly acid soils and become more soluble as soil pH rises. These minerals would therefore be quite unstable in alkaline soils, but are prominent in acid soils, in which they are quite insoluble and stable.

Other similar compounds, combining phosphorus with iron, aluminum, or manganese, are also found in acid soils. Some are products of surface reactions between phosphate ions and the somewhat amorphous hydroxy polymers that often exist as coatings on soil particles. Evidence suggests that phosphate ions even react with aluminum near the edges of silicate clay crystals, forming insoluble products similar to the aluminum phosphates described in the preceding paragraph.

Effect of Aging on Inorganic Phosphate Availability

In both acid and alkaline soils, phosphorus tends to undergo sequential reactions that produce phosphorus-containing compounds of progressively lower solubility. Therefore, the longer that phosphorus remains in the soil, the less soluble—and, therefore, less plant-available—it tends to become. Usually, when soluble phosphorus is added to a soil, a rapid reaction removes

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BOX 14.2

PHOSPHORUS REMOVAL FROM WASTEWATER

Environmental soil scientists and engineers remove phosphorus from municipal wastewater by taking advantage of some of the same reactions that bind phosphorus in soils. After primary and secondary sewage treatment that removes solids and oxidizes most of the organic matter, tertiary treatment in huge, specially designed tanks (Figure 14.20*a*) causes phosphorus to precipitate through reactions with iron or aluminum compounds, such as the following:

$$\underset{\text{Alum}}{Al_2(SO_4)_3 \cdot 14H_2O} + 2PO_4^{3-} \rightarrow 2AlPO_4 + \underset{\text{Soluble phosphate}}{3SO_4^{2-}} + \underset{\text{Insoluble AlP}}{14H_2O} \quad (14.2)$$

$$\underset{\text{Ferric chloride}}{FeCl_3} + \underset{\text{Soluble phosphate}}{PO_4^{3-}} \rightarrow \underset{\text{Insoluble FeP}}{FePO_4} + 3Cl^- \quad (14.3)$$

The insoluble aluminum and iron phosphates settle out of solution and are later mixed with other solids from the wastewater to form sewage sludge. The low-phosphorus water, after additional processing, is returned to the river.

Other less-expensive tertiary treatment approaches involve the spraying of the wastewater on vegetated soils. Natural soil and plant processes clean the phosphorus and other constituents out of the waste water. In some *infiltration* systems, the water percolates through relatively permeable soils.

As the following example illustrates, knowledge of soil properties and processes is essential for effective design of advanced land-based wastewater treatment systems. A large environmental engineering firm won a contract to build a new type of wastewater treatment facility that would look more like a park than a sewage plant because it used constructed wetlands and soils to clean the wastewater. After flowing through a number of artificial marshes and filtering systems (Figure 14.20*b*), the wastewater was sprayed into a large field covered with a layer of artificial permeable "soil" several meters thick (Figure 14.20*c*). The expectation was that the phosphorus would be fixed as it moved through the "soil," lowering the phosphorus concentration to a level that allowed the water to be released into a nearby estuary.

Unfortunately, the system didn't work. The water coming from the bottom of the artificial soil profile was *higher* in phosphorus than before the treatment! The problem? The designers had specified peat (see Box 12.5), an organic material very low in mineral colloids, as the artificial "soil" through which the water percolated. Consequently, insufficient iron, aluminum, or calcium compounds were available to fix the phosphorus. Soil scientists brought in to assist the municipality recognized the problem and recommended that a few train carloads of steel wool dust (metallic iron) be incorporated into the peat. As the steel wool rusted (oxidized), ferric iron formed and reacted strongly with the dissolved phosphorus in the wastewater. The phosphorus was precipitated without appreciably decreasing the desirable high permeability of the peat "soil."

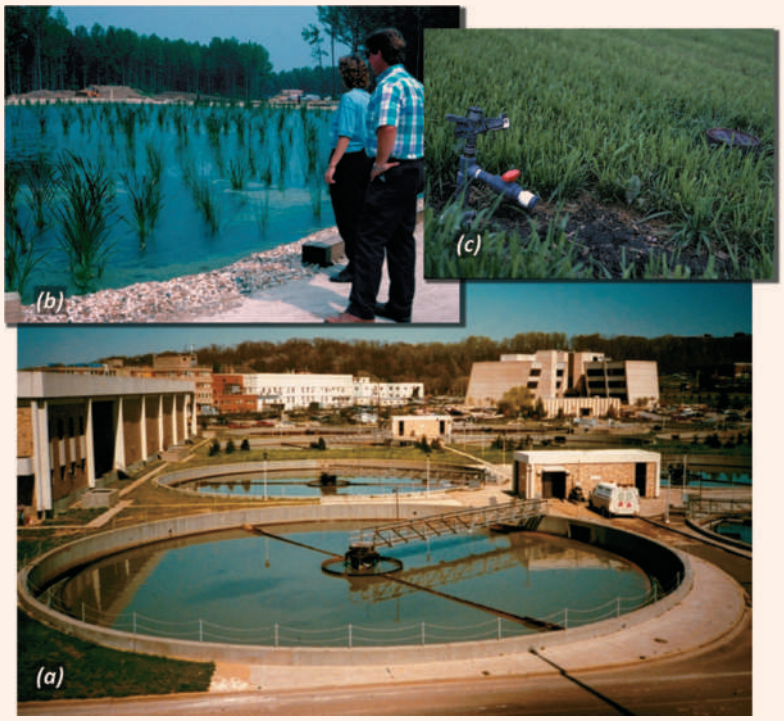

Figure 14.20 *Modern sewage plants (a) include tertiary treatment facilities for phosphorus removal by chemical precipitation with alum or iron chloride. Some phosphorus removal can also occur when partially treated effluent is passed through an artificial wetland (b) to remove nitrogen by denitrification (see Chapter 13). The effluent from the wetland is then sprinkled on a grass covered field (c) so that it can be further purified as it percolates through an engineered peat soil. Steel wool was mixed into the peat soil to supply iron surfaces that react with and remove any phosphorus from the percolating water.* (Photos courtesy of Ray R. Weil)

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Table 14.5
INORGANIC PHOSPHORUS-CONTAINING COMPOUNDS IMPORTANT FOR SOILS
In each group, the compounds are listed in order of increasing solubility.

Compound	Formula
Iron and aluminum compounds	
Strengite	$FePO_4 \cdot 2H_2O$
Variscite	$AlPO_4 \cdot 2H_2O$
Calcium compounds	
Fluorapatite	$[3Ca_3(PO_4)_2] \cdot CaF_2$
Carbonate apatite	$[3Ca_3(PO_4)_2] \cdot CaCO_3$
Hydroxy apatite	$[3Ca_3(PO_4)_2] \cdot Ca(OH)_2$
Oxyapatite	$[3Ca_3(PO_4)_2] \cdot CaO$
Tricalcium phosphate	$Ca_3(PO_4)_2$
Octacalcium phosphate	$Ca_8H_2(PO_4)_6 \cdot 5H_2O$
Dicalcium phosphate	$CaHPO_4 \cdot 2H_2O$
Monocalcium phosphate	$Ca(H_2PO_4)_2 \cdot H_2O$
Magnesium compound	
Struvite	$NH_4MgPO_4 \cdot 6H_2O$

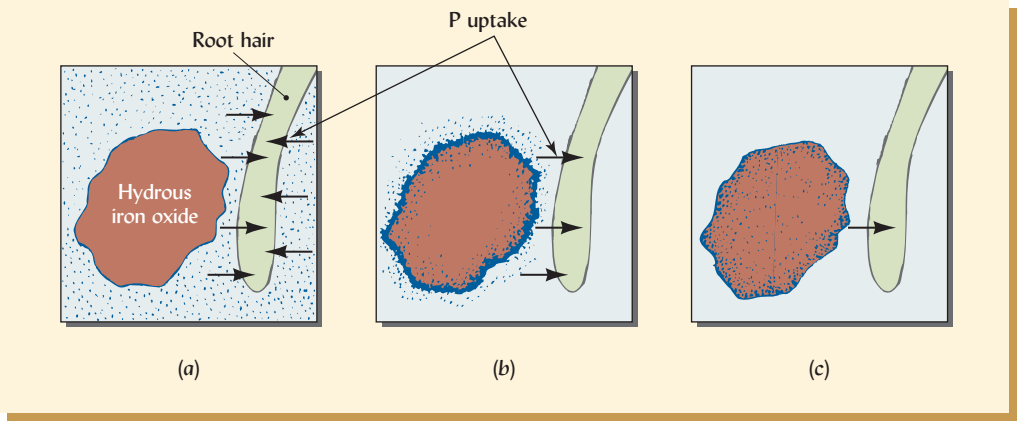

Figure 14.21 *How relatively soluble phosphates are rendered unavailable by such soil components as hydrous oxides of Fe and Al. (a) The situation just after application of a soluble phosphate. The root hair and the hydrous iron oxide particle are surrounded by soluble phosphate ions (small dots). (b) Within a very short time most of the soluble phosphate has reacted with the surface of the iron oxide crystal. The phosphorus is still somewhat available to the plant roots, since most of it is located at the surface of the particle where exudates from the plant can encourage exchange. (c) In time the phosphorus penetrates the crystal, and only a small portion is found near the surface. Under these conditions its availability is very low.*

the phosphorus from solution (*fixes* the phosphorus) in the first few hours. Slower reactions then continue to gradually reduce phosphorus solubility for months or years as the phosphate compounds age. The freshly fixed phosphorus may be slightly soluble and of some value to plants. With time, the solubility of the fixed phosphorus tends to decrease to extremely low levels. The effect of aging appears to be due to such factors as the regularity and size of crystals in precipitated phosphates, more permanent bonding of adsorbed phosphate into the calcium carbonate or metal oxide particles, and the extent to which sorbed phosphate is buried as surface precipitation reactions continue (Figure 14.21). The nature of these and other reactions of phosphorus in soils is discussed in the following sections.

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14.6 SOLUBILITY OF INORGANIC SOIL PHOSPHORUS

The particular types of reactions that fix phosphorus in relatively unavailable forms differ from soil to soil and are closely related to soil pH (Figure 14.22). In acid soils these reactions involve mostly Al, Fe, or Mn, either as dissolved ions, oxides, or hydrous oxides. Many soils contain such hydrous oxides as coatings on soil particles and as interlayer precipitates in silicate clays. In alkaline and calcareous soils, the reactions primarily involve precipitation as various calcium phosphate minerals (see Table 14.5) or adsorption to the iron impurities on the surfaces of carbonates and clays. At moderate pH values, adsorption on the edges of kaolinite or on the iron oxide coating on kaolinite clays plays an important role.

Precipitation by Iron, Aluminum, and Manganese Ions

Probably the easiest type of phosphorus-fixation reaction to visualize is the simple reaction of $H_2PO_4^-$ ions with dissolved Fe^{3+}, Al^{3+}, and Mn^{3+} ions to form insoluble hydroxy phosphate precipitates (Figure 14.23*a*). In strongly acid soils, enough soluble Al, Fe, or Mn is usually present to cause the chemical precipitation of nearly all dissolved $H_2PO_4^-$ ions by reactions such as the following (using the aluminum cation as an example):

$$\underset{\text{(soluble)}}{Al^{3+} + H_2PO_4^- + 2H_2O} \rightleftharpoons 2H^+ + \underset{\text{(insoluble)}}{Al(OH)_2H_2PO_4} \qquad (14.4)$$

Freshly precipitated hydroxy phosphates are slightly soluble because they have a great deal of surface area exposed to the soil solution. Therefore, the phosphorus contained in them is, initially at least, somewhat available to plants. Over time, however, as the precipitated hydroxy phosphates age, they become less soluble and the phosphorus in them becomes almost completely unavailable to most plants.

Reaction with Hydrous Oxides and Silicate Clays

Most of the phosphorus fixation in acid soils probably occurs when $H_2PO_4^-$ ions react with, or become adsorbed to, the surfaces of insoluble oxides of iron, aluminum, and manganese, such as gibbsite ($Al_2O_3 \cdot 3H_2O$) and goethite ($Fe_2O_3 \cdot 3H_2O$; see Figure 14.23) and with 1:1 type silicate clays. These hydrous oxides occur as crystalline and noncrystalline particles and as coatings on the interlayer and external surfaces of clay particles. Fixation of phosphorus by clays probably takes place over a relatively wide pH range (see Figure 14.22). The large quantities of Fe, Al oxides and 1:1 clays present in many soils make possible the fixation of extremely large amounts of phosphorus by these reactions.

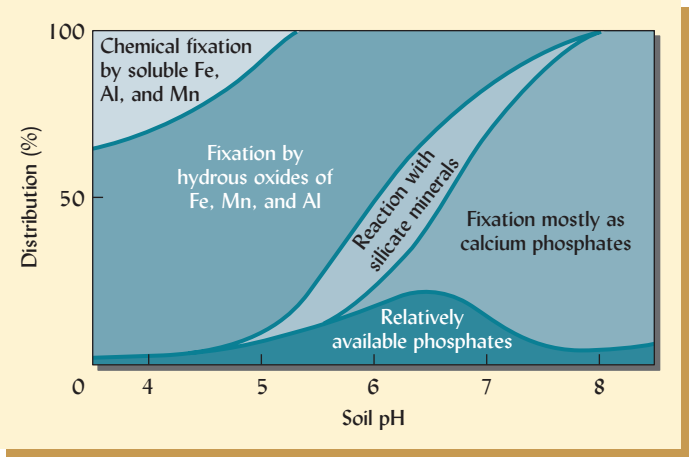

Figure 14.22 *Inorganic fixation of added phosphates at various soil pH values. Average conditions are represented and any particular soil would have a somewhat different distribution. The actual proportion of the phosphorus remaining in an available form will depend upon contact with the soil, time for reaction, and other factors. It should be kept in mind that some of the added phosphorus may be changed to organic forms in which it would be temporarily unavailable but subject to mineralization.* (Diagram courtesy of N. Brady and Ray R. Weil)

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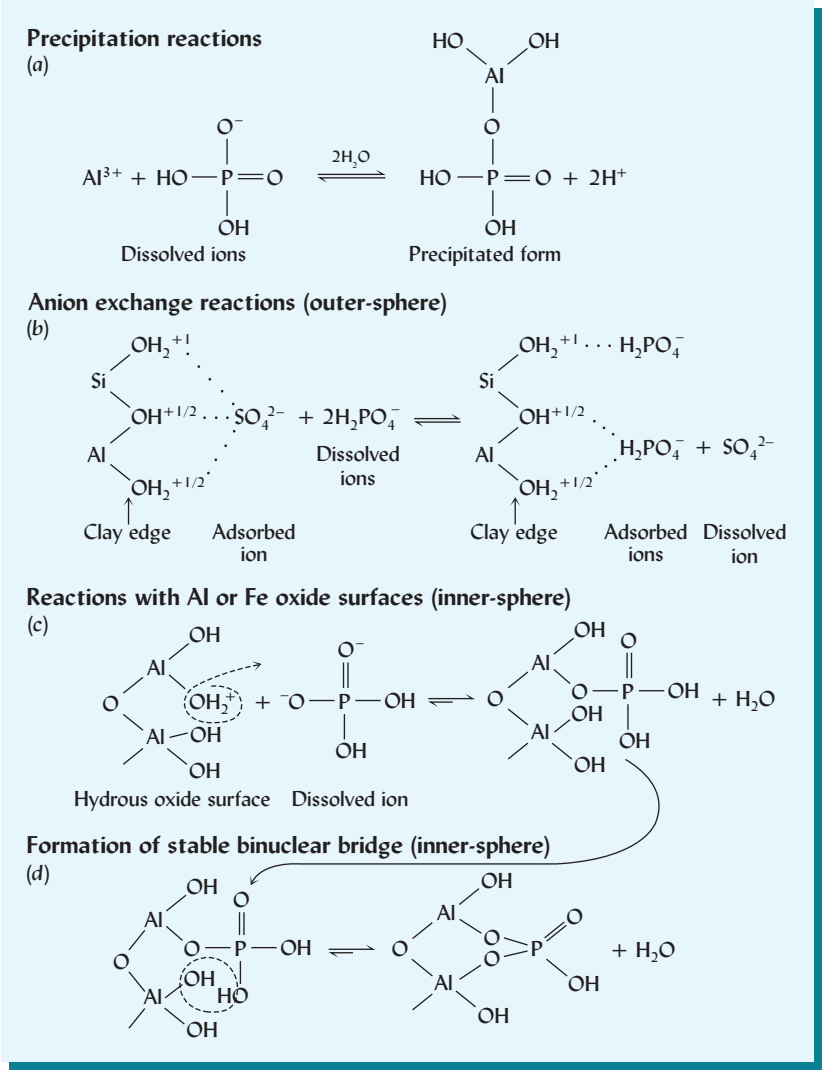

Figure 14.23 *Several of the reactions by which phosphate ions are removed from soil solution and fixed by the iron and aluminum in various hydrous oxides. Freshly precipitated aluminum, iron, and manganese phosphates (a) are relatively available, though over time they become increasingly unavailable. In (b) the phosphate is reversibly adsorbed by anion exchange. In reactions of the type shown in (c) a phosphate ion replaces an —OH_2 or an —OH group in the surface structure of Al or Fe hydrous oxide minerals. In (d) the phosphate further penetrates the mineral surface by forming a stable binuclear bridge. The adsorption reactions (b–d) are shown in order from those that bind phosphate with the least tenacity to the most tenacity (from the most to the least reversible and plant-available). Phosphate ions added to a soil may undergo this entire sequence of these reactions, becoming increasingly unavailable. Note that (b) illustrates an outer-sphere complex, while (c) and (d) are examples of inner-sphere complexes (see Figure 8.25).* (Diagram courtesy of Ray R. Weil)

Although all the exact mechanisms have not been identified, $H_2PO_4^-$ ions are known to react with iron and aluminum mineral surfaces in several different ways, resulting in different degrees of phosphorus fixation. Some of these reactions are shown diagrammatically in Figure 14.23.

The $H_2PO_4^-$ anion may be attracted to positive charges that develop under acid conditions on the surfaces of iron and aluminum oxides and the broken edges of kaolinite clays (see Figure 14.23*b*). The adsorbed $H_2PO_4^-$ anions form outer-sphere complexes and are subject to anion exchange with certain other anions, such as OH^-, SO_4^{2-}, MoO_4^{2-}, or organic acids (R—COO^-; see Section 8.7). Since this type of adsorption of $H_2PO_4^-$ ions is reversible, the phosphorus may slowly become available to plants. Availability of such adsorbed $H_2PO_4^-$ may be increased by: (1) liming the soil to increase the hydroxyl ions, or (2) adding organic matter to increase organic acids (anions) capable of replacing $H_2PO_4^-$.

The phosphate ion may also replace a structural hydroxyl to form an inner-sphere complex with the oxide (or clay) surface (see Figure 14.23*c*). This reaction, while reversible, binds the phosphate too tightly to allow its ready replacement by other anions. The availability of phosphate bound in this manner is very low. Over time, a second oxygen of the phosphate ion may replace a second hydroxyl, so that the phosphate becomes chemically bound to two adjacent aluminum (or iron) atoms in the hydrous oxide surface (see Figure 14.23*d*). With this step, the phosphate becomes an integral part of the oxide mineral, and the likelihood of its release back to the soil solution is extremely small.

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Finally, as more time passes, the precipitation of additional iron or aluminum hydrous oxide may bury the phosphate deep inside the oxide particle (see Figure 14.21). Such phosphate is termed *occluded* and is the least available form of phosphorus in most acid soils.

Precipitation reactions similar to those just described are responsible for the rapid reduction in availability of phosphorus added to soil as soluble $Ca(H_2PO_4)_2 \cdot H_2O$ in fertilizers (Figure 14.24). As already mentioned, (see Box 14.2) this type of reaction can also be used to control the solubility of phosphorus in wastewater.

Effect of Iron Reduction Under Wet Conditions

Phosphorus bound to iron oxides by the mechanisms just discussed is very insoluble under well-aerated conditions. However, prolonged anaerobic conditions can reduce the iron in these complexes from Fe^{3+} to Fe^{2+}, making the iron–phosphate complex much more soluble and causing it to release phosphorus into solution. The release of phosphorus from iron phosphates by means of the reduction and subsequent solubilization of iron improves the phosphorus availability in soils used for paddy rice.

These reactions are also of special relevance to water quality. Phosphorus bound to soil particles may accumulate in underwater sediments, along with organic matter and other debris. As the sediments become anoxic, the reducing environment may cause the gradual release of phosphorus held by hydrous iron oxides. Thus, the phosphorus eroded from soils today may aggravate the problem of eutrophication for years to come, even after the erosion and loss of phosphorus from the land has been brought under control.

Reaction with Calcium and Magnesium Compounds in Alkaline Soils[7]

In alkaline soils (e.g., pH = 8), soluble $H_2PO_4^-$ quickly reacts with calcium to form a sequence of products of decreasing solubility. For instance, highly soluble monocalcium phosphate [$Ca(H_2PO_4)_2 \cdot H_2O$] added as concentrated superphosphate fertilizer rapidly reacts with calcium carbonate in the soil to form first dicalcium phosphate ($CaHPO_4 \cdot 2H_2O$) and then tricalcium phosphate [$Ca_3(PO_4)_2$], as follows:

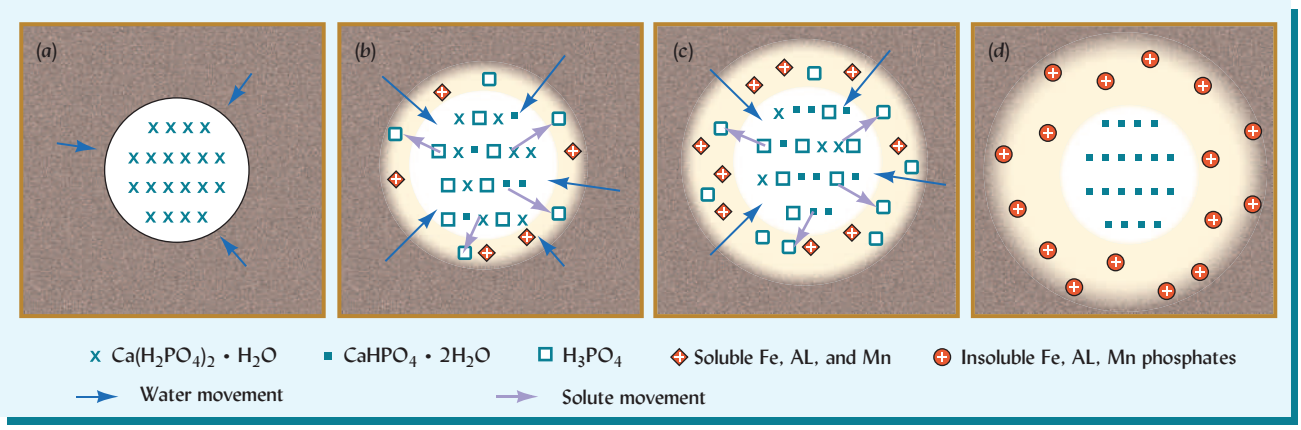

Figure 14.24 *When a granule of soluble calcium monophosphate [$Ca(H_2PO_4)_2 \cdot H_2O$] fertilizer is added to moist soil, the following series of reactions rapidly reduces the availability of the added phosphorus: (a) The $Ca(H_2PO_4)_2 \cdot H_2O$ (x) in the fertilizer granule attracts water from the soil. (b) In the moistened granule, phosphoric acid is formed by the following reaction: $Ca(H_2PO_4)_2 \cdot H_2O + H_2O \rightarrow CaHPO_4 \cdot 2H_2O + H_3PO_4$. As more water is attracted, an H_3PO_4-laden solution with a pH of about 1.4 moves outward from the granule. (c) This acid solution dissolves and displaces large quantities of iron, aluminum, and manganese. These ions promptly react with the phosphate to form low-solubility compounds. (d) Later, these compounds revert to the hydroxy phosphates of iron, aluminum, and manganese in acid soils. In neutral to alkaline soils, equally insoluble calcium phosphates are formed. In both cases, insoluble dicalcium phosphate ($CaHPO_4 \cdot 2H_2O$) remains in the granule (□). Fortunately, the phosphorus in the freshly precipitated compounds is slightly available for plant uptake. But when these freshly precipitated compounds are allowed to age or to revert to more insoluble forms, the phosphorus becomes almost completely unavailable to plants in the short term.* (Diagram courtesy of Ray R. Weil)

[7]See Devau et al. (2009) for a discussion of the effect of pH on phosphorus reactions in soil.

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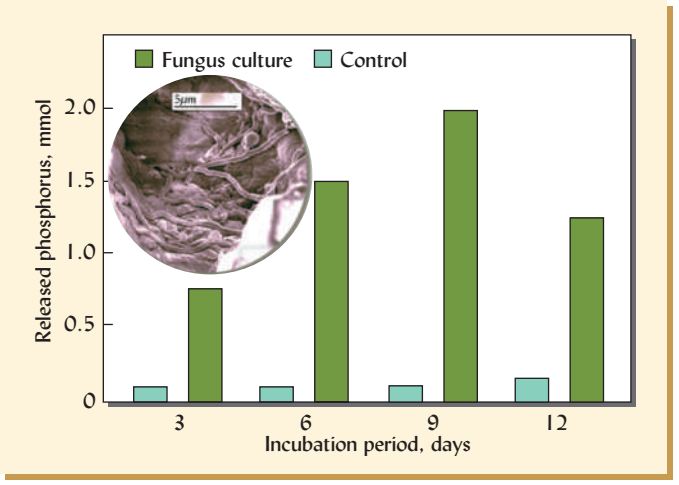

Figure 14.25 *Certain soil microorganisms can increase the availability of phosphorus in minerals such as phosphate rock and aluminum phosphates that normally hold the phosphorus in very insoluble forms.* (inset) *A micrograph of a fungus growing on an aluminum phosphate soil surface. The fungus is thought to produce organic acids that help solubilize phosphorus.* (bar graph) *In another experiment, phosphorus is released from phosphate rock by a fungus* (Aspergillus niger) *that had been isolated from a tropical soil.* [Micrograph (inset) courtesy of Dr. Anne Taunton, University of Wisconsin; bar graph drawn from data in Goenadi et al. (2000)]

$$\underset{\text{Monocalcium phosphate (soluble)}}{Ca(H_2PO_4)_2 \cdot H_2O} + 2H_2O \xrightarrow{CaCO_3} \underset{\text{Dicalcium phosphate (slightly soluble)}}{2(CaHPO_4 \cdot 2H_2O)} + CO_2\uparrow \xrightarrow{CaCO_3} \underset{\text{Tricalcium phosphate (very low solubility)}}{Ca_3(PO_4)_2} + CO_2\uparrow + 5H_2O \tag{14.5}$$

The solubility of these compounds and, in turn, the plant availability of the phosphorus they contain decrease as the phosphorus changes from the $H_2PO_4^-$ ion to tricalcium phosphate [$Ca_3(PO_4)_2$]. Although this compound is quite insoluble, it may undergo further reactions to form even more insoluble compounds, such as the hydroxy-, oxy-, carbonate-, and fluor-apatites shown in Table 14.5. These compounds are thousands of times less soluble than freshly formed tricalcium phosphates. Because of these solubility relationships powdered phosphate rock (which consists mainly of apatite minerals) may be an effective source of phosphorus for plants in strongly acid soils, while the same material would likely be of little utility if used on neutral or alkaline soils.

Because of the various reactions with $CaCO_3$, phosphorus availability tends to be nearly as low in the Aridisols, Inceptisols, and Mollisols of arid regions as in the highly acid Spodosols, Ultisols, and Oxisols of humid regions, where iron, aluminum, and manganese limit phosphorus availability.

Biological Influences on Solubility of Inorganic Phosphorus Compounds in Soils

Certain bacteria and fungi enhance the solubility of both calcium and iron and aluminum phosphates by releasing citric and other organic acids. These acids either dissolve the calcium phosphates or form metal complexes that release the P from iron and aluminum phosphates (Figure 14.25). The released P is likely used first by the microorganisms themselves, but is eventually made available to plants as well (see Section 14.8).

14.7 PHOSPHORUS-FIXATION CAPACITY OF SOILS

The phosphorus-fixation capacity of a soil may be conceptualized as the total number of sites capable of reacting with phosphate ions to "fix" them in unavailable, insoluble forms. The fixation reactions include all of the sorption and precipitation reactions just discussed in Section 14.6. The concept of a finite phosphorus-fixation capacity for a soil is illustrated schematically in Figure 14.26.

One way of determining the phosphorus-fixing capacity of a particular soil is to shake a known quantity of the soil in a phosphorus solution of known concentration. After about

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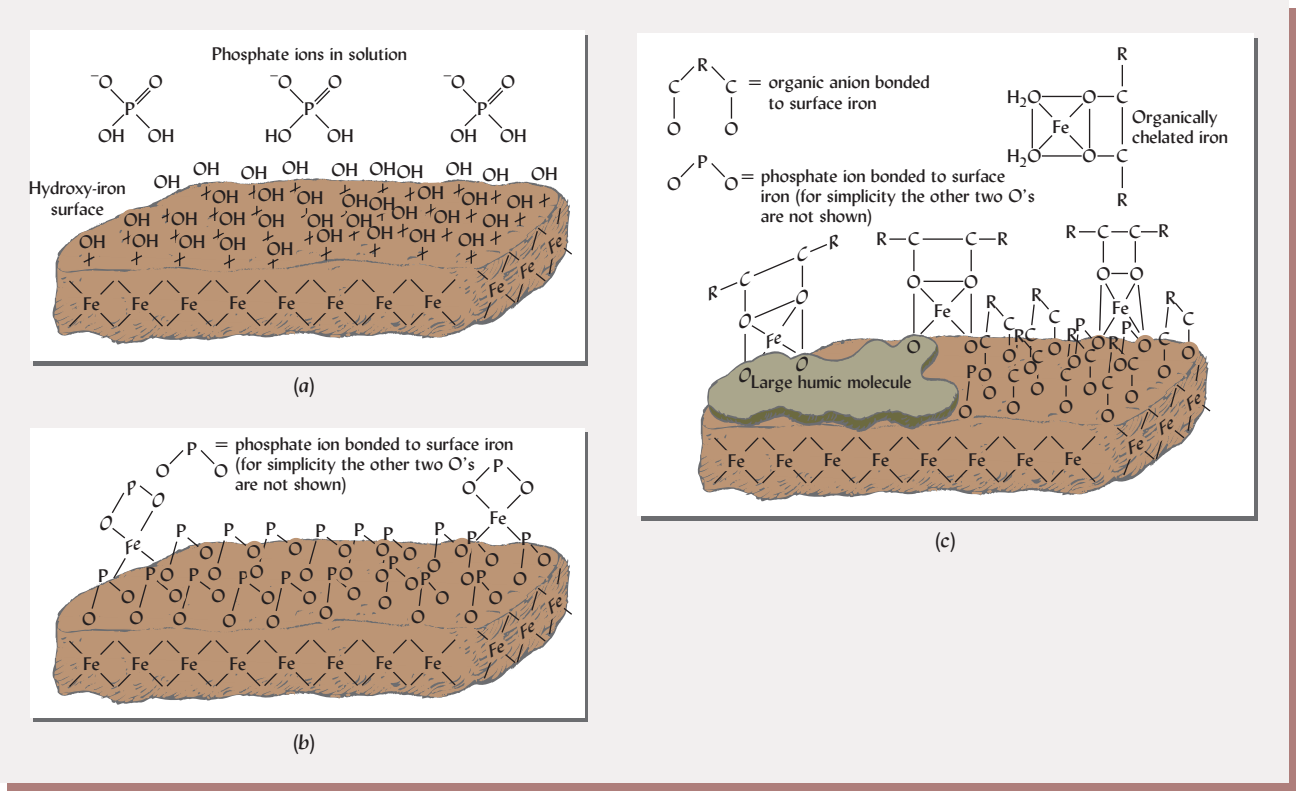

Figure 14.26 *Schematic illustrations of phosphorus-fixation sites on a soil particle surface showing hydrous iron oxide as the primary fixing agent. In part (a) the sites are shown as + symbols, indicating positive charges or hydrous metal oxide sites, each capable of fixing a phosphate ion. In part (b) the fixation sites are all occupied by phosphate ions (the soil's fixation capacity is satisfied). Part (c) illustrates how organic anions, larger organic molecules, and certain strongly fixed inorganic anions can reduce the number of sites available for fixing phosphorus. Such mechanisms partially account for the reduced phosphorus fixation and greater phosphorus availability brought about when mulches and other organic materials are added to a soil.*
(Diagram courtesy of Ray R. Weil)

24 hours an equilibrium will be approached, and the concentration of phosphorus remaining in the solution (the **equilibrium phosphorus concentration** [EPC]) can be determined. The difference between the initial and final (*equilibrium*) solution phosphorus concentrations represents the amount of phosphorus fixed by the soil. If this procedure is repeated using a series of solutions with different initial phosphorus concentrations, the results can be plotted as a phosphorus-fixation curve (sometimes referred to as a P fixation isotherm, if temperature is held constant, Figure 14.27). The maximum phosphorus-fixation capacity can be extrapolated from the value at which the curve levels off.

Phosphorus fixation by soils is not easily reversible. However, if a portion of the fixed phosphorus is present in relatively soluble forms (see Section 14.6) and most of the fixation sites are already occupied by a phosphate ion, some release of phosphorus to solution is likely to occur when the soil is exposed to water with a very low phosphorus concentration. This release (often called *desorption*) of phosphorus is indicated in Figure 14.27 where the curve for soil A crosses the zero fixation line and becomes negative (negative fixation = release). The solution EPC_0 is the equilibrium phosphorus concentration (x-axis) at which zero fixation occurs (phosphorus is neither released nor retained). The EPC_0 is an important parameter for both soil fertility and environmental assessment because it indicates: (1) the capacity to replenish the soil solution as it is depleted of P by plant roots, and (2) the rate at which the soil will release phosphorus into runoff and leaching waters.

Quantity-Intensity Relationships.[8] The relationship between phosphorus in solution and phosphorus in slowly soluble or fixed forms is an example of the balance between *quantity*

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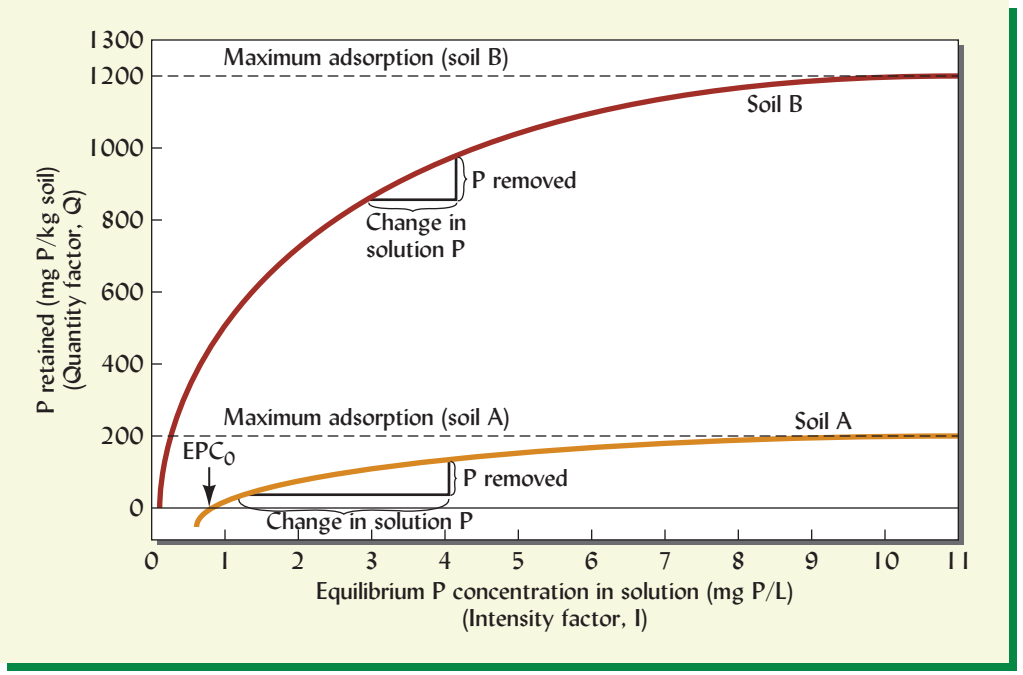

Figure 14.27 *The relationship between phosphorus fixed and phosphorus remaining dissolved when two different soils (A and B) are shaken in solutions of various initial phosphorus concentrations. Each soil removes nearly all of the phosphorus from low concentration solutions. However, when solutions are used that contain so much phosphorus that most of the phosphorus-fixation sites become occupied, a larger portion of the phosphorus remains in solution. The amount fixed by the soil levels off as the* maximum phosphorus-fixing capacity *of the soil is reached (see horizontal dashed lines: for soil A, 200 mg P/kg soil; for soil B, 1200 mg P/kg soil). If the initial phosphorus concentration of a solution is equal to the* equilibrium phosphorus concentration (EPC) *for a particular soil, that soil will neither remove phosphorus from nor release phosphorus to the solution (i.e., phosphorus fixation = 0 and EPC = EPC_0). If the solution phosphorus concentration is less than the EPC_0, the soil will release some phosphorus (i.e., the fixation will be negative). In this example, soil B has a much* higher *phosphorus-fixing capacity and a much* lower *EPC than does soil A. It can also be said that soil B is highly* buffered *because much phosphorus must be added to this soil to achieve a small increase in the equilibrium solution phosphorus concentration.* (Diagram courtesy of Ray R. Weil)

factors and *intensity* factors in soil fertility. The intensity factor is the amount of a nutrient dissolved in the soil solution. The quantity factor is the amount of that nutrient associated with the solid framework of the soil and in equilibrium with the nutrient ions in solution. In Figure 14.27, the intensity factor would be represented on the x-axis and the quantity factor on the y-axis. The slope of the curve that defines the relationship for each soil represents the amount of change in the quantity factor Q that results from a given change in the intensity factor I; that is, slope $= \Delta Q/\Delta I$. This is another way of expressing the *potential buffering capacity* (PBC) of the soil:

$$\text{PBC} = \frac{\Delta Q}{\Delta I} \tag{14.6}$$

This general relationship applies not only to phosphorus, but to potassium and any other substance whose solution concentration is controlled by retention reactions with the soil solids. In Section 9.4, for example, buffering of pH was discussed.

Factors Affecting the Extent of Phosphorus Fixation in Soils. Soils that remove more than 350 mg P/kg of soil (i.e., a phosphorus-fixing capacity of about 700 kg P/ha in surface soil) from solution are generally considered to be high phosphorus-fixing soils. High phosphorus-fixing soils tend to maintain low phosphorus concentrations in the soil solution and in runoff water.

[8]For a review of buffering capacity as it relates to the available phosphorus and potassium, as well as other nutrients, see Nair (1996).

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Table 14.6 lists values of maximum phosphorus-fixing capacity for a range of soils. The effects of clay content and type of clay are apparent. These and other factors will now be discussed.

Amount of Clay Present. Most of the compounds with which phosphorus reacts are in the finer soil fractions. Therefore, if soils with similar pH values and mineralogy are compared, phosphorus fixation tends to be more pronounced, and ease of phosphorus release tends to be lowest in those soils with higher clay contents.

Type of Clay Minerals Present. Some clay minerals are much more effective at phosphorus fixation than others. Generally, those clays that possess greater anion exchange capacity (due to positive surface charges) have a greater affinity for phosphate ions. For example, extremely high phosphorus fixation is characteristic of allophane clays typically found in Andisols and other soils associated with volcanic ash. Oxides of iron and aluminum, such as gibbsite and goethite, also strongly attract and hold phosphorus ions. Among the layer silicate clays, kaolinite has a greater phosphorus-fixation capacity than most. The 2:1 clays of less-weathered soils have relatively less capacity to bind phosphorus. Thus, the soil components responsible for phosphorus-fixing capacity are, in order of increasing extent and degree of fixation:

$$\text{2:1 clays} \ll \text{1:1 clays} < \text{carbonate crystals} < \text{crystalline Al, Fe, Mn oxides} < \text{amorphous Al, Fe and Mn oxides, allophane}$$

To some degree, the preceding phosphorus-fixing soil components are distributed among soils in relation to soil taxonomy. Vertisols and Mollisols generally are dominated by 2:1 clays and have low phosphorus-fixation capacities unless they are calcareous. Iron and aluminum oxides are prominent in Ultisols and Oxisols. Andisols, characterized by large quantities of amorphous oxides and allophane, have the greatest phosphorus-fixing capacity, and their productivity is often limited by this property (Figure 14.28).

Effect of Soil pH. The greatest degree of phosphorus fixation occurs at very low and very high soil pH. As pH increases from below 5.0 to about 6.0, the iron and aluminum phosphates become somewhat more soluble. Also, as pH drops from greater than 8.0 to below 6.0, calcium phosphate compounds increase in solubility. Therefore, as a general rule in mineral

Table 14.6
MAXIMUM PHOSPHORUS-FIXATION CAPACITY OF SOILS WITH DIFFERENT CLAYS
Fe, Al oxides (especially amorphous types) fix the largest quantities and silicate clays (especially 2:1-type) fix the least.

Soil classification (and series, if known)	Location	Clay		Maximum P fixation, mg P/kg soil
		Percent	Type	
Katikwe-Wera (Orthox)	Uganda	6	Kaolinite, Fe, Al oxides	89
Evesboro (Quartzipsamment)	Maryland, USA	6	Kaolinite, Fe, Al oxides	125
Kandiustalf	Zimbabwe	20	Kaolinite, Fe oxides	394
Kitsap (Xerept)	Washington, USA	12	2:1 clays, allophane	453
Matapeake (Hapludult)	Maryland, USA	15	Chlorite, kaolinite, Fe oxides	465
Miesso (Uderts)	Ethiopia	59	2:1 clays, kaolinite	714
Harare (Rhodustalf)	Zimbabwe	5	Kaolinite, Fe oxides	737
Newberg (Haploxeroll)	Washington, USA	38	2:1 clays, Fe oxides	905

Washington data from Kuo (1988); Uganda and Ethiopia from Mamo and Wortmann (2009); Maryland and Zimbabwe data courtesy of Ray R. Weil and F. Folle (unpublished).

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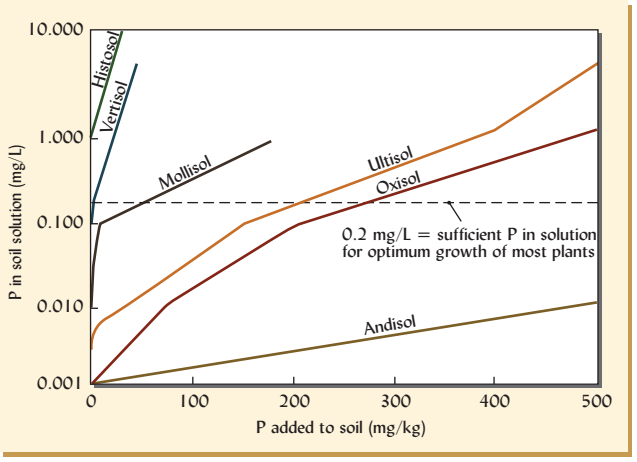

Figure 14.28 *Typical soil solution levels of phosphorus when increasing amounts of fertilizer phosphorus are added to representative soils from several different orders. Without help from mycorrhizal fungi, most crop plants require a concentration of about 0.2 mg/L in the soil solution for optimum growth (see Table 14.7). The graph suggests very low phosphorus-fixing capacities of Histosols and Vertisols, making it possible for soils in these orders when initially cultivated to require little if any fertilizer to support good plant growth. In contrast, because of their high phosphorus-fixing capacities, unfertilized Ultisols and Oxisols would require a minimum of 200–300 kg P/ha for good plant growth, and Andisols would require many times this amount. Curves are representative of data from many sources and would not necessarily apply for a given soil in each order. P fixation could be increased if the soil has been long cultivated fertilizer or decreased if the soil has been so heavily fertilized with phosphorus that much of the soil's P-fixing capacity may already be satisfied.* (Diagram courtesy of Ray R. Weil)

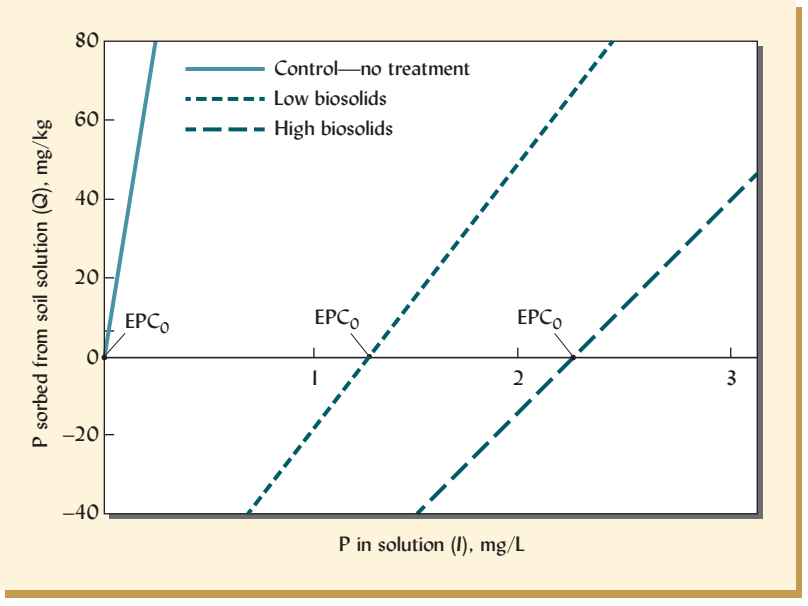

Figure 14.29 *Phosphorus quantity/intensity (Q/I) relationships for a Mollisol without and with two rates of organic amendment (sewage biosolids). Note that the phosphorus in solution for the untreated soil remains very low, even when 80 mg P/kg soil has been sorbed. When biosolids were added to the soil, however, much higher phosphorus is maintained in solution. At lower solution phosphorus values, the amount sorbed (Q) was negative, indicating release from (instead of sorption to) the soil. The high EPC_0 indicates easy access to P for plant nutrition, but also that P may be easily lost from the treated soil by leaching and runoff leading to downstream eutrophication.* [From Sui and Thompson (2000)]

soils, phosphate fixation is at its lowest (and plant availability is highest) when soil pH is maintained in the 6.0–7.0 range (see Figure 14.22).

Even if pH ranges from 6.0 to 7.0, phosphate availability may still be very low, and added soluble phosphates will be readily fixed by soils. The low recovery by plants of phosphates added to field mineral soils in a given season is partially due to this fixation. A much higher recovery would be expected in organic soils (see Histosol, Figure 14.28) and in many potting mixes where calcium, iron, and aluminum concentrations are not as high as in mineral soils.

Effect of Organic Matter. Organic matter has little capacity to strongly fix phosphate ions. To the contrary, amending soil with organic matter, especially decomposable material, is likely to reduce phosphorus fixation by several mechanisms (see Figure 14.26). First, large, organic molecules adhering to sorbing surfaces can mask fixation sites and prevent them from interacting with phosphorus ions in solution. Second, organic acids produced by plant roots and microbial decay can serve as organic anions, which compete with phosphorus ions for positively charged sites on the surfaces of clays and hydrous oxides. Third, certain organic compounds can entrap reactive Al and Fe in stable organic complexes called *chelates* (see Section 15.8). Once chelated, the metals are unavailable for reaction with phosphorus ions in solution. In addition, phosphorus fixation is also likely reduced by the release of phosphorus ions by microbial mineralization of many P-rich organic materials. Figure 14.29 illustrates that added

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organic material (in this case, treated sewage sludge termed *biosolids*) reduces the Q/I ratio (slope of sorption curve) and increases EPC_0 (level of phosphorus in solution).

14.8 PLANT STRATEGIES FOR ADEQUATE PHOSPHORUS ACQUISITION FROM SOILS[9]

Because of the low supply of soil phosphorus and the many P-fixation reactions just discussed, terrestrial plants have had to evolve special mechanisms or strategies for obtaining the phosphorus they need. Knowledge of these strategies can help us understand ecological relationships and develop more effective plant-soil management practices. Although much remains to be learned, we can say that different plant species enhance phosphorus uptake using at least six basic strategies (Figure 14.30):

1. When roots encounter low phosphorus soil they may produce more and longer branch roots and an abundance of root hairs. These responses greatly increase the absorptive surface area available for P uptake.
2. Roots of certain species may exude specific organic compounds (e.g., citric, malic, malonic, oxalic, piscidic, and tartaric acids) that complex with iron or aluminum and thus release the phosphorus from insoluble Fe/Al-phosphates. For example, roots of pigeon pea plants are known to excrete *piscidic acid* that strongly complexes with Fe to greatly increase their ability to access iron-bound soil phosphorus in the highly weathered tropical soils of their native habitat.
3. Roots of some plants acidify their rhizosphere to speed the dissolution of sparingly soluble Ca-phosphate compounds. For example, because most N-fixing legumes use little nitrate from the soil, they take up a large excess of cations over anions, leading to the release of H^+ ions and pronounced rhizosphere acidification (see Figure 14.31 and Section 9.1).
4. Roots may exude enzymes (phosphatases) that can cleave the phosphate group from organic compounds, especially in dissolved organic P, making the phosphorus available for root uptake.

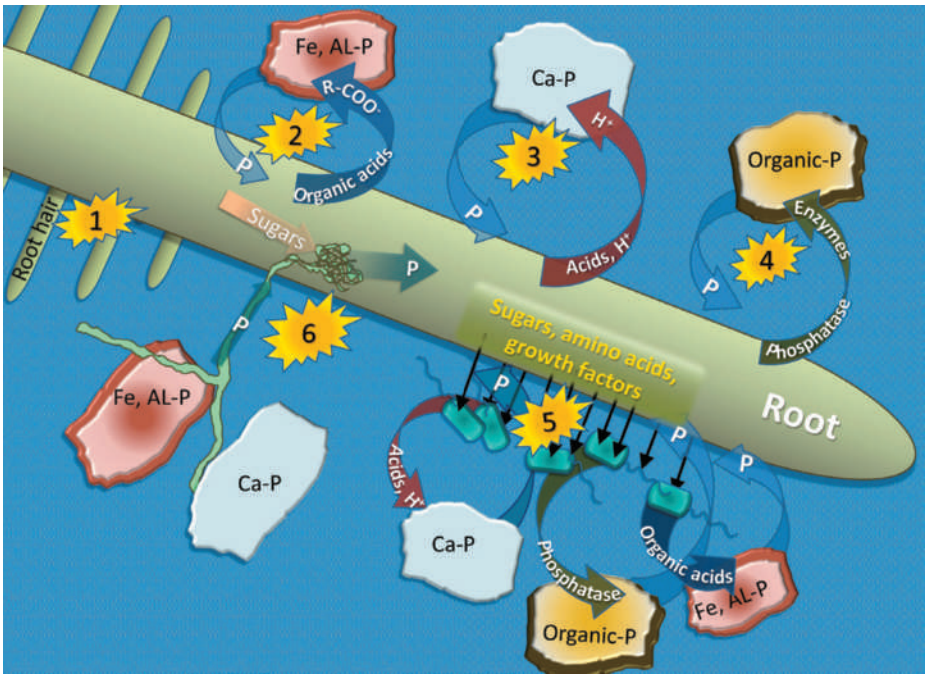

Figure 14.30 *Six basic strategies that plant roots may employ to enhance their uptake of various forms of phosphorus from soils. (1) Increased root absorptive surface area. (2) Chelate iron or aluminum to release P. (3) Dissolve Ca–P compounds with acid exudates (4) Exude phosphatase enzymes to release P from organic compounds. (5) Exude substances to stimulate P-solubilizing rhizobacteria. (6) Encourage colonization by mycorrhizal fungi that help plants take up P.* (Diagram courtesy of Ray R. Weil)

[9]The Virtual Fertilizer Research Center has published several reviews aimed at stimulating innovations in this arena (Koele et al., 2014; Smit et al., 2013). For ways to more efficiently use phosphorus resources by applying the chemical and biological process discussed in this chapter, see also Frossard et al. (2000).

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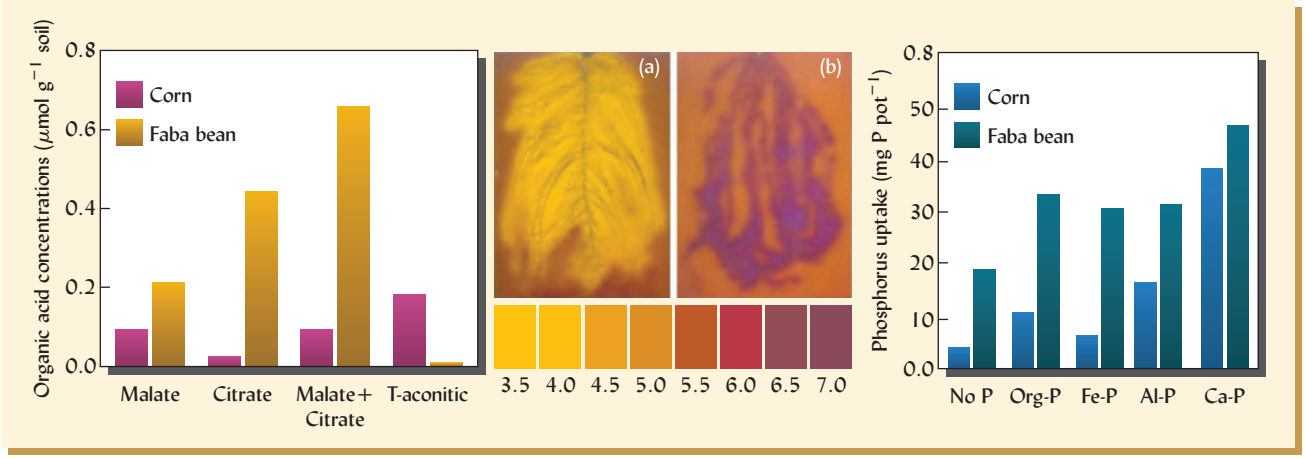

Figure 14.31 *The capacities of legume (faba bean) and grass (corn) plants to increase the availability of phosphorus from various low-solubility sources.* (Left) *The concentration of various organic acid root exudates measured in the rhizosphere soil from corn and faba beans growing in low-phosphorus sandy soil.* (Center) *Roots of faba bean* (a) *and corn* (b) *after 6 hours growing in gel medium without phosphorus but impregnated with bromocresol pH color indicator visually illustrates the acidification of the rhizosphere by the faba bean and the alkalization by the corn.* (Right) *Phosphorus uptake by faba bean and corn growing in pots of soil amended with no P, with organic (inositol hexaphosphate) P, with* $FePO_4$, *with* $AlPO_4$, *or with* $Ca(H_2PO_4)_2$, *highly soluble calcium monophosphate fertilizer. Field and pot experiments in this research suggested that corn growing in alternate rows with faba bean could benefit from the enhanced P availability from faba bean rhizosphere activity.* [Graphic made from material in Li et al. (2007)]

5. Some roots exude growth-stimulating substances that attract and/or enhance the growth of rhizobacteria or fungi, which in turn excrete, organic acids, chelating compounds, or enzymes that release soluble orthophosphate by attacking various phosphorus compounds in the soil.
6. Some plants use root exudates as signaling compounds that attract and encourage colonization by mycorrhizal fungi. The plants then invest some of their sugars from photosynthesis as "payment" to these fungi for "phosphorus delivery services" (see Sections 14.3 and 11.9). Even on soils moderately well supplied with phosphorus, there is commonly a close relationship between degree of root colonization by effective mycorrhizal fungi and the amount of P taken up by the plant (Figure 14.32). Researchers have found that plants invest more energy into their mycorrhizal relationship if the soil is low in P, and that some plants can discriminate between effective and ineffective mycorrhizal fungi by "paying" more for better "service."

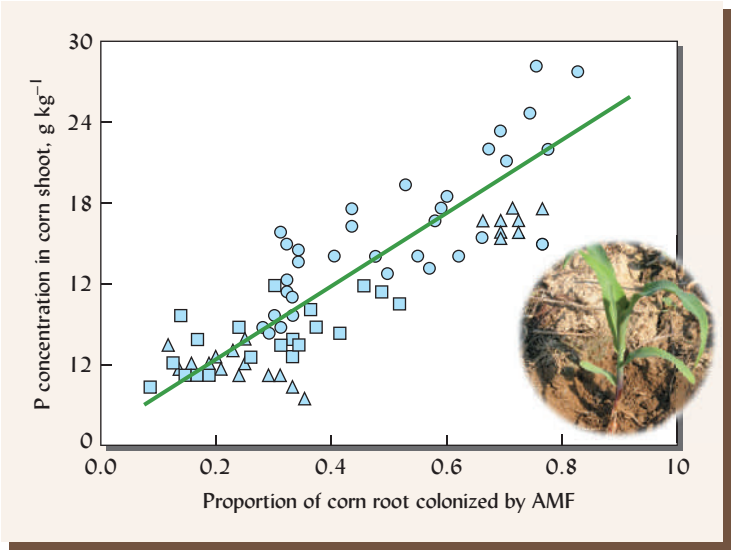

Figure 14.32 *Even on a soil with relatively high amounts of plant-available phosphorus, increased colonization by mycorrhizal fungi is associated with increased levels of P in young corn crop seedlings.* [Graph based on data from White and Weil (2009)]

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Many plant species deploy a combination of several of these strategies. For example, plants in the Brassica family (cabbage, mustard, radish, etc.) compensate for their very poor to no mycorrhizal colonization by excreting citric and malic acids, forming extensive fine root hairs, and taking up high amounts of Ca^{2+} (which acidifies the rhizosphere and accelerates the dissolution of Ca-phosphates by mass action). Certain legumes, such as faba bean, in addition to forming strong symbiotic relationships with mycorrhizal fungi, also exude organic acids and phosphatase enzymes enabling access to P in Fe/Al phosphates and organic compounds (Figure 14.31, *right*).

Knowledge of these plant characteristics can aid in choosing plants for ecosystem restoration, as well as for farmers who need to make more efficient use of phosphorus soil reserves and fertilizers in low-phosphorus soils.

14.9 PRACTICAL PHOSPHORUS MANAGEMENT

The principles of soil phosphorus behavior discussed in this chapter suggest a number of management strategies to address the twin problems of too little and too much of this critical element. On one hand, the challenge is to maximize the efficiency by which plants obtain phosphorus from low-P soils. On the other hand, the challenge is to avoid wasting this finite and precious resource (Box 14.3) and to keep it from polluting aquatic systems.

Management Strategies for Meeting Plant Phosphorus Needs in Low-P Soils

Enhance Mycorrhizal Symbiosis. Practices that enhance mycorrhizal symbiosis usually improve the utilization of soil phosphorus. One such practice is to include in the plant community or crop rotation plant species that are effective hosts for mycorrhizal fungi (Figure 14.32). It is also important to minimize tillage disruption of hyphal networks in the soil, and in some highly disturbed soils, to inoculate with appropriate fungi (see Section 11.9).

P-Efficient Plants. Some plant species require much less phosphorus in the soil solution than do others. Table 14.7 indicates the requirements of several agricultural species, but there are also wide differences among native plants. To better utilize finite P resources plant scientists will need to breed varieties or select species with the ability to thrive in soil with low levels of phosphorus supply and solubility.

Adjust P Application to Soil Status. Where phosphorus-fixing capacity is grossly unsaturated, optimum crop yields will likely require additions that considerably exceed plant uptake. However, as the excess phosphorus begins to saturate fixation sites, rates of application should be lowered to supply no more than what plants take up so as to prevent excessive phosphorus accumulations.

Localized Placement. Phosphorus fertilizer concentrated in a localized zone of soil is less likely to undergo fixation reactions (Figure 14.24) than fertilizer mixed into the bulk soil. Localized placement thereby reduces the amount of fertilizer required. This end can be achieved by placing fertilizer in narrow bands alongside plant rows or in small holes next to individual plants and by the use of pellets instead of fine powders. In untilled systems of randomly spaced plants (grasslands and forests), broadcasting on the soil surface effectively creates a vertically localized "band," but one that may be subject to loss in surface runoff.

Combine Ammonium with Phosphorus. When ammonium and phosphorus fertilizers are mixed in a band, the acidity produced by oxidation of ammonium ions (see Section 13.7) and by uptake of excess cations as ammonium (see Section 9.1) keeps the phosphate in more soluble compounds and enhances plant P uptake.

Control of Soil pH. Phosphorus availability can be optimized in most soils by proper liming or acidification (see Sections 9.8 and 9.10) to a pH level between 6 and 7.

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BOX 14.3

PEAK PHOSPHORUS?[a]

Many scientists argue that improving the efficiency of phosphorus use in farming is not only essential for profitable agriculture, but is a moral obligation to future generations that will have to depend on Earth's limited phosphorus supplies. The immediacy of this concern is not shared by everyone, but the importance of conserving phosphorus is based on two facts that are quite indisputable: (1) phosphorus has *no* substitute and (2) it is *not* a renewable resource.

All living things require phosphorus as it is *literally* in their DNA. Humans need phosphorus in their own diets. Soils need phosphorus if they are to support the plants and animals we use for food. There is no substitute for phosphorus in these roles. Economists tell us that generally goods will be replaced by something else if scarcity drives up prices. For example, if copper becomes too expensive, fiber optic cables might replace copper wires; or if fossil fuels become too expensive, people may invest in wind power to replace oil and gas in generating electricity. Since phosphorus is a basic chemical element in the structure of many essential cellular components (DNA, RNA, membranes, ATP), no such substitution will be possible.

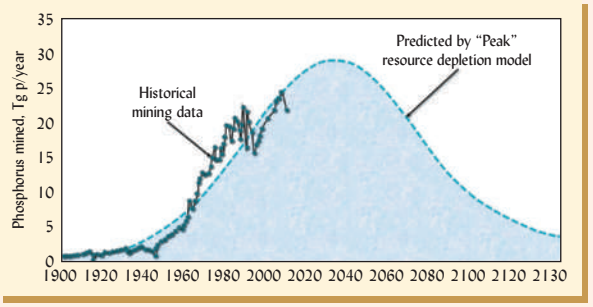

FIGURE 14.33 *World historical and modeled trends for mined phosphorus production illustrating the concept of a peak in production occurring when somewhat more than half of the total reserves have been depleted.* [Modified from Cordell and White (2011)]

Phosphorus is a nonrenewable resource—and one that is in quite limited supply, both in absolute global amounts and in geographic distribution. The vast majority of the world's minable phosphorus is in the North African country of Morocco. Historical examples and current resource theory suggest that as the best, easiest to mine deposits get used up first, the remaining resources get harder and more expensive to mine and refine. Thus accelerating resource exploitation to meet growing demand will eventually be limited first by escalating costs and then by dwindling absolute supply, resulting in a maximum or peak rate of production when just over half of the total resource has been used up (Figure 14.33). The remaining deposits will continue to be mined for decades beyond that time, but in ever smaller amounts and at ever greater expense. While there is considerable disagreement about the actual size of world phosphate reserves and how long they will last if extraction technology improves (estimates range between 100 and 500 years to exhaustion), the data suggest peak production will come much sooner than once thought—perhaps during this century. Hence there is growing sense of urgency among many scientists and policy makers (see, e.g., the European effort at http://www.phosphorusplatform.eu/).

On the positive side, the same phosphorus atoms can be used over and over again—if they are not so carelessly dispersed as to make them virtually unrecoverable. The current model is unsustainable. We mine phosphorus and apply it as soluble fertilizer only to have much of it wash off P-saturated farmland into streams and then into lakes and oceans. Even most of the phosphorus that crops do take up and use makes its way indirectly to the oceans after a one-way trip through the food to sewage system. For these reasons—not to even mention the damage P causes in eutrophication of aquatic systems—there is a growing belief that the time has come for individuals and societies to learn more efficient and sustainable methods of using our infinitely precious but definitely finite phosphorus resource.

[a]For reviews of the complex issues and varying estimates involved with Peak Phosphorus concept, see Cordell and White (2015) and Scholz et al.(2015). For perspectives on the "trilemma" involving geopolitics, poverty, and resource limitations, see Obersteiner et al. (2013) and Wyant et al. (2013).

Cycling of Organic Matter. During the microbial breakdown of organic materials, phosphorus is released slowly and can be taken up by plants or mycorrhizae before it can be fixed by the soil. In addition, organic compounds can reduce soil P fixation capacity (Figure 14.26). Residues or prunings from certain phosphorus-efficient plants (e.g., the African shrub *Tithonia diversifolia*) can be harvested from a donor site and transferred to a low-fertility receiving site where phosphorus will be supplied as the transferred plant material decays.

Use of P-Efficient Cover Crops. Highly P-efficient plants grown as cover crops solubilize and take up phosphorus from the soil profile and incorporate it into their tissues. When the cover crop is killed, the plant tissues decompose, and the contained phosphorus is released into the surface soil, where it can be easily used by less efficient plants that follow in rotation (Figure 14.34).

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Table 14.7
SOIL SOLUTION PHOSPHORUS CONCENTRATION REQUIRED FOR 95% MAXIMUM GROWTH OF VARIOUS PLANTS

Plant	Approximate P in soil solution, mg/L
Cassava	0.005
Peanut	0.01
Corn	0.05
Sorghum	0.06
Cabbage	0.04
Soybean	0.20
Tomato	0.20
Head lettuce	0.30

Based on selected data in from Fox (1981).

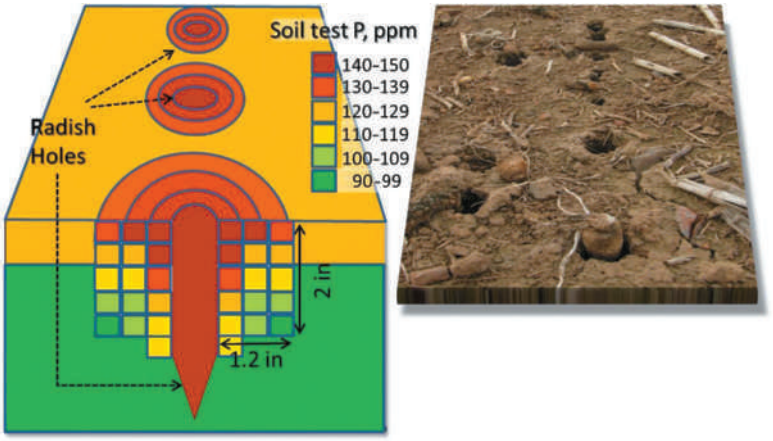

Figure 14.34 *Localized concentration and increased plant availability of soil phosphorus as a result of the growth, nutrient uptake, and subsequent decay of a tap-rooted cover crop (forage radish).* (Left) *Diagram of soil P concentrations as determined by Mehlich3 soil test (see Section 16.11).* (Right) *A photograph shows the decaying roots and root holes left by a similar forage radish cover crop after it had winter-killed.* [Diagram from data in White and Weil (2011); photo courtesy of Ray R. Weil]

Management Strategies for Controlling Overenrichment of Soils and Water Pollution

Avoid Excess Accumulation. This goal requires carefully keeping the sum of all phosphorus inputs (deposition, fertilizers, organic amendments, plant residues, and animal feed) from consistently exceeding plant removals or accumulating beyond the lowest levels that will support near-optimum plant growth (see Sections 14.3 and 16.12). In cases where soils are already overenriched with phosphorus, an effort should be made to remove the excess through intensive production and harvest export of high P-content crops without further P additions.

Minimize Loss in Runoff and Eroded Sediment. Use of conservation tillage practices that minimize runoff and erosion, *especially from land already high in phosphorus*, is essential. Cover crops and plant residues can increase infiltration and reduce runoff (see Section 6.2). Application of manure or fertilizer to frozen soils should be avoided, and application by injection into the soil rather than broadcasting on the surface should be implemented (see Section 16.8).

Capture P from Runoff. Natural or constructed wetlands (Section 7.7) and perennially vegetated riparian (shoreline) buffer strips (Section 16.2) can tie up some phosphorus before runoff enters sensitive lakes or streams. These measures remove some dissolved P, but mainly P bound to sediment.

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Capture P from Drainage Water. In most soils phosphorus is quite immobile and leaching losses are normally very small. However, where certain agricultural soils have been artificially drained and overfertilized with phosphorous, significant quantities of both organic and inorganic P have been observed to leach through the upper soil profile and into drain tiles or ditches. In sandy soils with shallow water tables, leaching occurs mainly because the P-fixation capacity of the soil has been saturated in much of the profile. In finer textured soils, cracks, worm holes, and root channels may connect water ponded on the soil surface directly to the drainage pipes (tile lines) installed about 1 m deep. Under flooded and saturated conditions (see Section 6.8), preferential flow down these macro pores may carry P in solution or fixed to suspended soil particles. One strategy for controlling such losses is to managed drainage flows so they occur only when needed. Another approach is to use iron-, aluminum-, or calcium-containing compounds as chemical filters in drainage ditches to precipitate phosphorus and remove it from drainage water.

Tie Up P with Inorganic Compounds. Various iron-, aluminum-, or calcium-containing materials will react with dissolved P from phosphorus saturated soils or P-rich organic waste products. Highly insoluble compounds are formed, similar to those described in Section 14.5 and Box 14.2. Treating poultry litter in the chicken house with aluminum sulfate (alum) and spreading inorganic amendments on the surface of cropped soils or grass sod are practices that greatly reduce the loss of phosphorus dissolved from P-rich organic amendments such as manure or compost (Figure 14.35). Application of about 2 Mg/ha of gypsum to the surface of artificially drained cropland with nonalkaline soils has been shown to greatly reduce the phosphorus lost in surface runoff as well as that lost through the drainage system (Figure 14.36). The gypsum acts by two mechanisms. The calcium in the gypsum reacts with dissolved P to form low solubility products (see Section 14.5) that remove P from the surface and subsurface runoff water. Second, calcium cations and associated increased ionic strength around gypsum particles enhances clay flocculation (see Section 10.6), reducing the dispersion and transport of clay—and its adsorbed phosphorus load—down soil macropores and across the soil surface.

14.10 POTASSIUM: NATURE AND ECOLOGICAL ROLES[10]

Of all the essential elements, potassium is taken up by plants in quantities second only to nitrogen, even exceeding nitrogen concentration in the leaves of some species. Although the total amount of potassium present in most soils is quite large, it is probably the nutrient that is the third or fourth most likely (after N, P, and probably S) to limit plant productivity. For this reason it is commonly applied to soils to enhance fertility and is a component of most so-called "complete" mixed fertilizers.

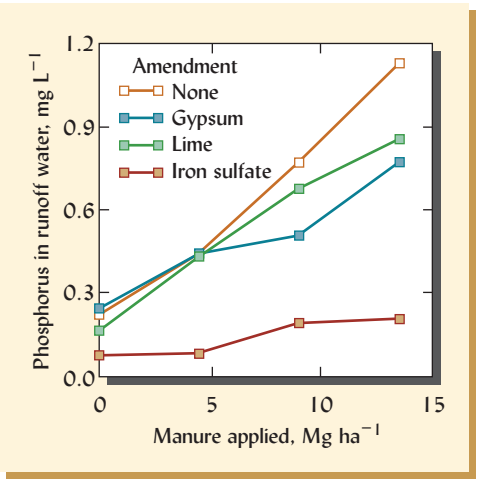

Figure 14.35 *Effect of surface application of iron sulfate, gypsum, or lime on the concentration of dissolved phosphorus in the first 10 minutes of runoff. Bermuda grass sod growing in boxes filled with clay textured A horizon soil (Haplustolls) was fertilized with composted dairy manure and subjected to simulated rain events. The iron sulfate quickly reacted with phosphate ions as they were released from the compost, forming highly insoluble iron phosphate compounds. Gypsum and lime, which formed some calcium-phosphates, were far less effective in reducing phosphorus in the runoff water, possibly because the manure and soil used were both already quite high in calcium.* [Drawn from data in Torbert et al. (2005)]

[10]For further information on this topic, see Mengel and Kirkby (2001) and Römheld and Kirkby (2010).

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Figure 14.36 *Gypsum applied to the soil surface can reduce phosphorus loss from some tile-drained croplands with fine-textured high-phosphorus soils. The photos illustrate the drainage water coming from two side-by-side fields (and bottled samples coming from similar fields), the one on the right having been treated with gypsum. This research in Ohio suggests that about 2 Mg of gypsum spread once every 2–3 years could reduce phosphorus losses by nearly 50% in both surface runoff and drainage water.* (Photos courtesy Warren Dick, The Ohio State University)

The potassium story differs in many ways from that of phosphorus. Unlike phosphorus (or sulfur and, to a large extent, nitrogen), potassium is present in the soil solution only as a positively charged cation, K^+. Like phosphorus, potassium does not commonly form any gases that could be lost to the atmosphere. Its behavior in the soil is influenced primarily by soil cation exchange properties (see Chapter 8) and mineral weathering (Chapter 2), rather than by microbiological processes. Unlike nitrogen and phosphorus, potassium causes no serious off-site environmental problems when it leaves the soil system. It is not toxic and does not cause eutrophication in aquatic systems. Its overuse can, however, reduce plant uptake of calcium and other essential cations and can negatively impact soil physical quality in a manner similar to sodium (Chapter 10), though to a lesser degree.

14.11 POTASSIUM IN PLANT AND ANIMAL NUTRITION

Although potassium plays numerous roles in plant and animal nutrition, it is not actually incorporated into the structures of organic compounds. Instead, potassium remains in the ionic form (K^+) in solution in the cell or acts as an activator for cellular enzymes. Potassium is known to activate over 80 different enzymes responsible for such plant and animal processes as energy metabolism, starch synthesis, nitrate reduction, photosynthesis, and sugar degradation. Certain plants, many of which evolved in sodium-rich semiarid environments, can substitute sodium or other monovalent ions to carry out some, but not all, of the functions of potassium.

As a component of the plant cytoplasmic solution, potassium plays a critical role in lowering cellular osmotic water potential, thereby reducing the loss of water from leaf stomata and increasing the ability of root cells to take up water from the soil (see Section 5.3 for a discussion of osmotic water potential). Potassium is essential for photosynthesis, for protein synthesis, for nitrogen fixation in legumes, for starch formation, and for the translocation of sugars. As a result of several of these functions, a good supply of this element promotes the production of plump grains and large tubers. The potassium content of normal, healthy leaf tissue can be expected to be in the range of 1–4% in most plants, similar to that of nitrogen but an order of magnitude greater than that of phosphorus.

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Potassium is especially important in helping plants adapt to environmental stresses. Sufficient potassium nutrition is linked to improved drought tolerance, improved winter-hardiness, and greater tolerance to insect pests (Figure 14.37). In the latter role, potassium fertilization is often an important component of integrated pest-management programs designed to reduce the use of toxic pesticides. Alleviation of potassium deficiency commonly is commonly observed to reduce the incidence and severity of both fungal and bacterial plant diseases (Figure 14.38) including bacterial blights, stem rots, leaf spots (in rice, cassava, peanut, beans), rusts (in wheat, tea), and seedling rots (damping off) caused by *Rhizoctonia solani*. The greater disease susceptibility of potassium deficient plants is likely a result of impaired physiology and thinner, weaker cell

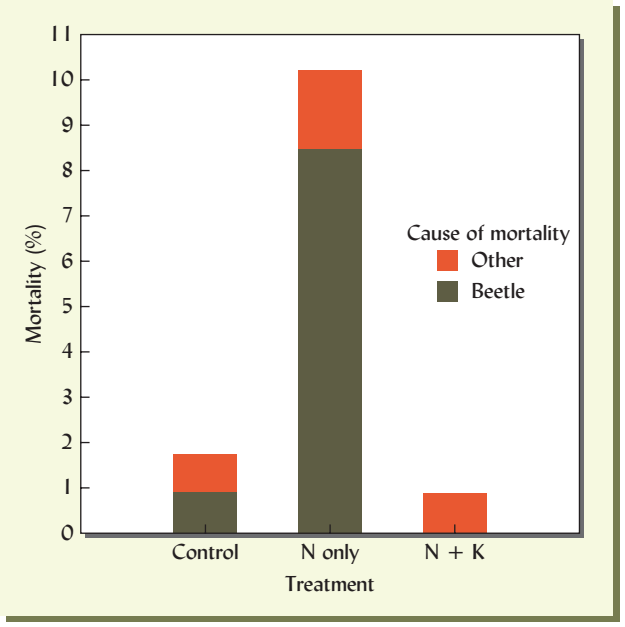

Figure 14.37 *Influence of potassium and nitrogen fertilizer treatments on the percentage of Ponderosa pine trees dying from beetle damage and other causes in the first four years after planting in western Montana, USA. Nitrogen used alone (224 kg N/ha) stimulated a large increase in tree mortality, but adding potassium (a single application of 224 kg K/ha) completely counteracted this effect. Both fertilization treatments stimulated the growth of the surviving trees.* [Redrawn from Garrison-Johnston et al. (2005)]

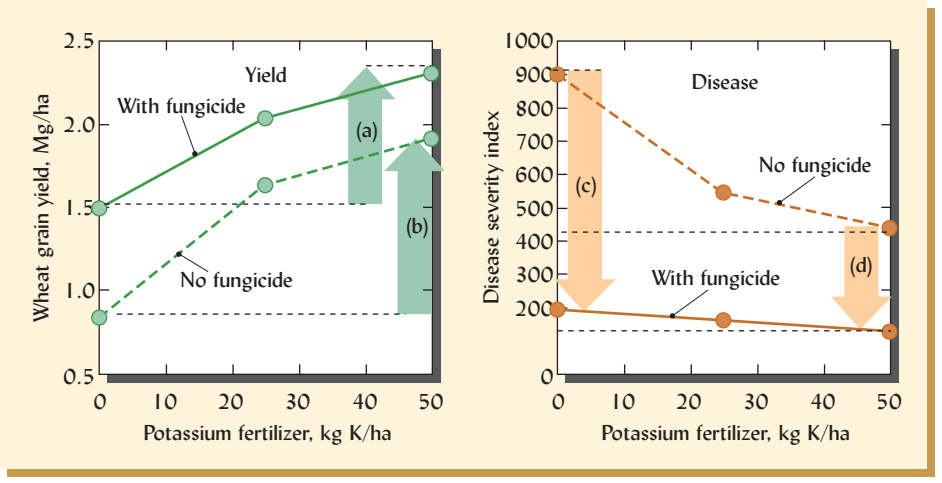

Figure 14.38 *Potassium fertilization on soils with low availability of this nutrient commonly reduces plant disease severity and increases yields. In warm South Asian wheat-growing regions,* Helminthosporium *leaf blight disease causes serious loss in wheat crops. Disease severity may be aggravated by deficiencies of soil nutrients, especially potassium. In this experiment in Nepal, alleviation of potassium deficiency reduced the disease severity almost as much as six to nine applications of the fungicide propiconazole. Arrows in the left panel indicate the effect of added K on wheat yield when the crop was (a) or was not (b) protected with fungicide sprays, suggesting that about one-half of the yield increase from K fertilization was related to enhanced disease resistance. Arrows in the right panel indicate the effect of the fungicide in reducing the disease severity without (c) or with (d) K fertilization. Data shown are means of two years and three wheat cultivars.* [Graphed from data in Sharma et al. (2005)]

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walls less resistant to pathogen penetration. In potassium deficient plants the synthesis of essential large molecules such as proteins, lignin, cellulose, and starch is reduced while simple organic compounds such as amides tend to accumulate. Application of potassium fertilizers beyond that needed to alleviate deficiency has not been shown to further reduce pest and disease problems.

Sufficient potassium nutrition also enhances the quality of flowers, fruits, and vegetables by improving flavor and color and strengthening stems (thereby reducing lodging). In many of these respects, potassium seems to counteract some of the detrimental effects of excess nitrogen. Maintaining a balance between potassium and other nutrients (especially nitrogen, phosphorus, calcium, and magnesium) is an important goal in managing soil fertility.

In animals, including humans, potassium plays critical roles in regulating the nervous system and in the maintenance of healthy blood vessels. Diets that include such high-potassium foods as bananas, potatoes, citrus, and leafy green vegetables have been shown to lower human risk of stroke and heart disease. Maintaining a balance between potassium and sodium is especially important in human diets.

Deficiency Symptoms in Plants

Compared to deficiencies of phosphorus and many other nutrients, a deficiency of potassium is relatively easy to recognize in most plants. In addition to the characteristics previously mentioned (reduced drought tolerance, increased lodging, etc.), specific foliar symptoms are associated with potassium deficiency. Because potassium is very mobile within the plant, it is translocated from older tissues to younger ones if the supply becomes inadequate. The symptoms of deficiency therefore usually occur earliest and most severely on the oldest leaves.

In general, when potassium is deficient tissue at the tips and edges of the oldest leaves begin to yellow (chlorosis) and then die (necrosis), so that the leaves appear to have been burned on the edges (Figure 14.39). On some plants the necrotic leaf edges may tear, giving the leaf a ragged appearance (Figure 14.39*a*,*b*,*g*). In several important forage and cover-crop legume species, potassium deficiency produces small, white necrotic spots that form a unique pattern along the leaflet margins; this easily recognized symptom is one that people often mistake for insect damage (see Figure 14.39*e*,*h*).

Potassium deficiency should not be confused with damage from excess salinity, which can also produce brown, necrotic leaf margins. Salinity damage is more likely to affect the newer leaves (see Figures 10.25 and 10.27).

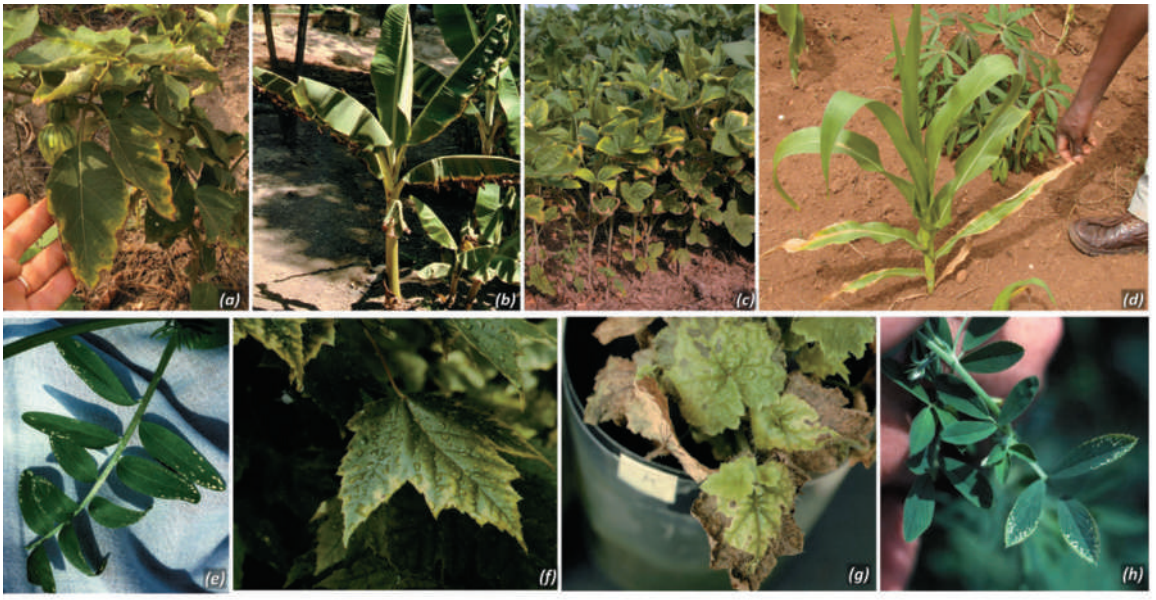

Figure 14.39 *Potassium deficiency often produces easily recognized foliar symptoms, mainly on older leaves: chlorotic margins on leaves of soybean (c), corn (d), and maple (f); ragged, necrotic margins of leaves on eggplant (a), banana (b), and piggyback plant (g); and small, white necrotic spots along edges of legume leaflets such on hairy vetch (e) and alfalfa (h).* (Photos courtesy of Ray R. Weil)

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14.12 THE POTASSIUM CYCLE

Figure 14.40 shows the major forms in which potassium is held in soils and the changes it undergoes as it is cycled through the soil–plant system. The original sources of potassium are the primary minerals, such as micas (biotite and muscovite) and potassium feldspar (orthoclase and microcline). As these minerals weather, their rigid lattice structures become more pliable. For example, potassium held between the 2:1-type crystal layers of mica is in time made more available, first as nonexchangeable but slowly available forms near the weathered edges of minerals and, eventually, as readily exchangeable ions and ions dissolved in the soil solution from which it is absorbed by plant roots.

Potassium is taken up by plants in large quantities. Depending on the type of ecosystem under consideration, a portion of this potassium is leached from plant foliage by rainwater (throughfall) and returned to the soil, and a portion is returned to the soil with the plant residues. In natural ecosystems, most of the potassium taken up by plants is returned in these ways or as wastes (mainly urine) from animals feeding on the vegetation. Some potassium is lost with eroded soil particles and in runoff water, and some is lost to groundwater by leaching. In agroecosystems, from one-fifth (e.g., in cereal grains) to nearly all (e.g., in hay crops) of the potassium taken up by plants may be exported from the field, commonly to distant markets, from which it is unlikely to return.

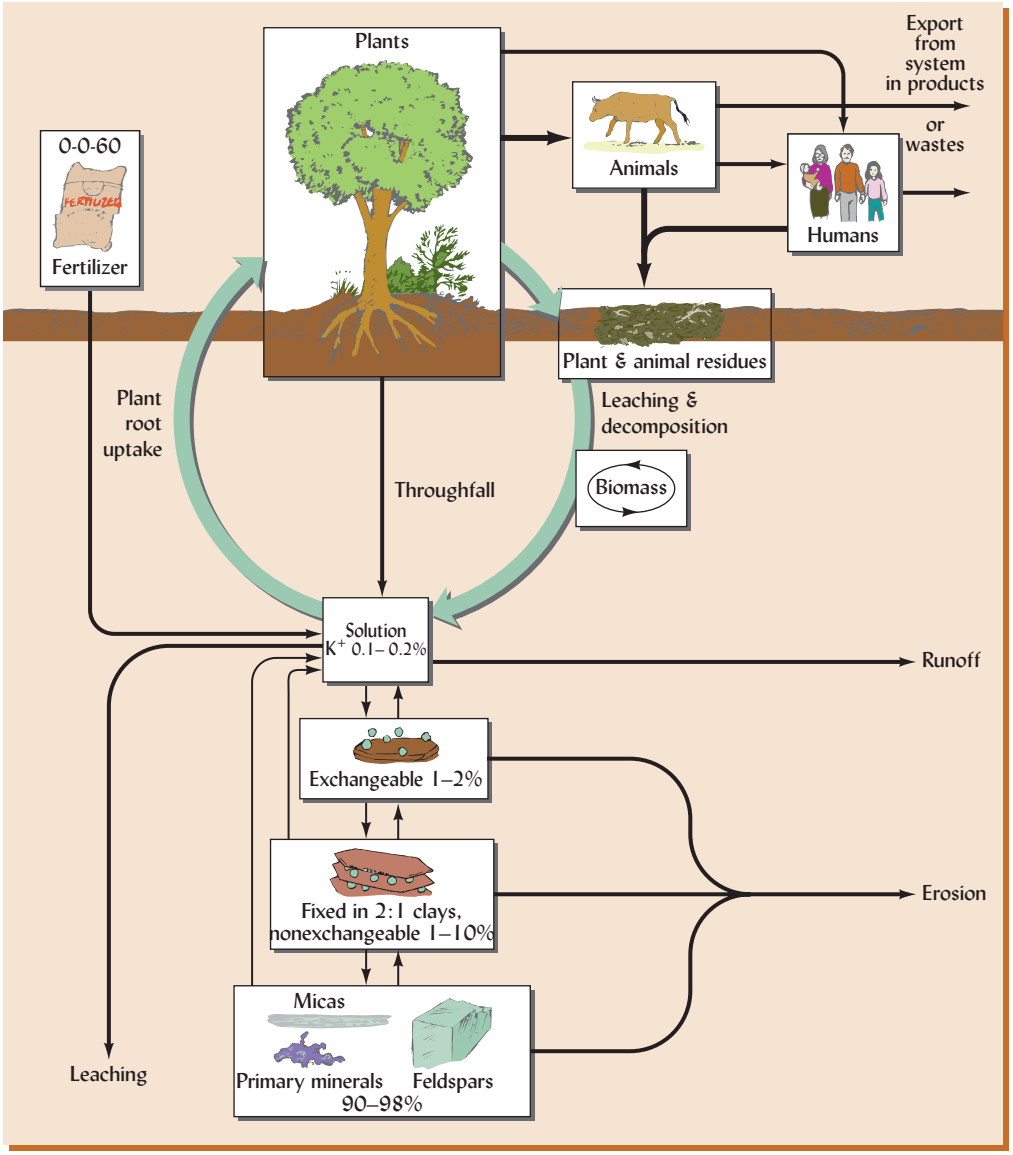

Figure 14.40 *Major components of the potassium cycle in soils. The large circular arrow emphasizes the biological cycling of potassium from the soil solution to plants and back to the soil via plant residues or animal wastes. Primary and secondary minerals are the original sources of the element. Exchangeable potassium may include those ions held and released by both clay and humus colloids, but potassium is not a structural component of soil humus. The interactions among solution, exchangeable, nonexchangeable, and structural potassium in primary minerals is shown. The bulk of soil potassium occurs in the primary and secondary minerals and is released very slowly by weathering processes.* (Diagram courtesy of Ray R. Weil)

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At any one time, most soil potassium is in primary minerals and nonexchangeable forms. In relatively young, fertile soils containing substantial amounts of weatherable minerals in the soil profile, the release of potassium from these forms to the exchangeable and soil solution forms that plants can use directly is usually sufficiently rapid to keep plants supplied with the potassium needed for optimum growth. On the other hand, where large amounts of high potassium content plant biomass are repeatedly removed from the land, or where the content of weatherable potassium-containing minerals is low, the levels of exchangeable and solution potassium may have to be supplemented by outside sources, such as chemical fertilizers, poultry manure, or wood ashes. On such inherently low potassium soils (especially quartz sands) potassium additions may be necessary to prevent the depletion of available potassium supplies and the resulting decline in productivity over a period of years.

An example of depletion and restoration of available soil potassium is illustrated in Figure 14.41. Farming without fertilizers for over a century depleted the exchangeable potassium in a sandy soil in New York, USA. After the supply of available potassium was exhausted, the land was abandoned in the 1920s. In the 1920s and 1930s a forest of red pines was planted. The trees in some plots were fertilized with potassium, causing the rapid recovery of exchangeable potassium to its pre-agricultural level, as expected. Even where the trees were not fertilized, the level of exchangeable potassium in the surface soil was replenished, but slowly, over a period of about 80 years.

The replenishment of exchangeable potassium in the unfertilized forest plots provides an example of the ability of unharvested perennial vegetation, such as forests and pastures, to restore soil fertility over time. Deep-rooted plants often act as "nutrient pumps," taking potassium (and other nutrients) from deep subsoil horizons into their root systems, translocating it to their leaves, and then recycling it back to the surface of the soil via leaf fall and leaching (see Section 16.3 and Figure 16.15).

In most mature natural ecosystems the small (1–5 kg/ha) annual losses of potassium by leaching and erosion are more than balanced by weathering of potassium from primary minerals and nonexchangeable forms in the soil profile, followed by vegetative translocation to the surface of the soil. In many agricultural annual cropping systems, leaching losses are far greater because much higher exchangeable K levels are maintained with fertilizers, while crop roots are active for only part of the year. The sections that follow give greater details on the reactions involved in the potassium cycle.

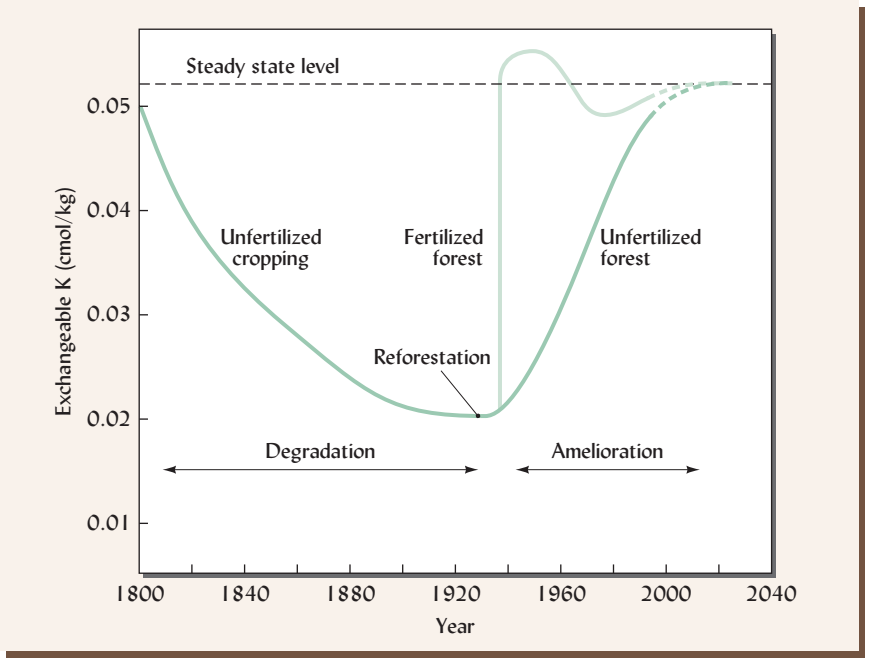

Figure 14.41 *The general pattern of depletion of A-horizon exchangeable potassium by decades of exploitative farming, followed by its restoration under forest vegetation. The forest consisted of red pine trees planted on a Plainfield loamy sand (Udipsamment) in New York, USA. This soil has a very low cation exchange capacity and low levels of exchangeable K^+.* [From Nowak et al. (1991)]

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14.13 THE POTASSIUM PROBLEM IN SOIL FERTILITY[11]

Availability of Potassium

In contrast to phosphorus, potassium is found in comparatively large amounts in most mineral soils, except those consisting mostly of quartz sand. In fact, the total quantity of this element is generally greater than that of any other major nutrient element. Amounts as great as 30,000–50,000 kg potassium in the upper 15 cm of 1 ha of soil are not at all uncommon (see Table 1.3), and the supplies of potassium in the subsoil layers are commonly many-fold greater.

Yet the quantity of potassium held in an easily exchangeable condition at any one time may be very small. Most of this element is held rigidly as part of the primary minerals or is fixed in forms that are, at best, only moderately available to many plants. Therefore, the situation with respect to potassium utilization parallels that of phosphorus and nitrogen in at least one way: A very large proportion of all three of these elements in the soil is insoluble and relatively unavailable to growing plants.

Leaching Losses

Potassium is much more readily lost by leaching than is phosphorus. Drainage waters from soils receiving liberal fertilizer applications usually contain considerable quantities of potassium. From representative humid-region soils growing annual crops and receiving only moderate rates of fertilizer, the annual loss of potassium by leaching is usually about 25–50 kg/ha, the greater values being typical of acid, sandy soils.

Losses would undoubtedly be much larger were the leaching of potassium not slowed by the attraction of the positively charged potassium ions to the negatively charged cation exchange sites on clay and humus colloids. Liming an acid soil to raise its pH can reduce the leaching losses of potassium because of the *complementary ion effect* (see Chapter 8 and Figure 14.42). The ease with which ions may be removed from the exchange complex varies

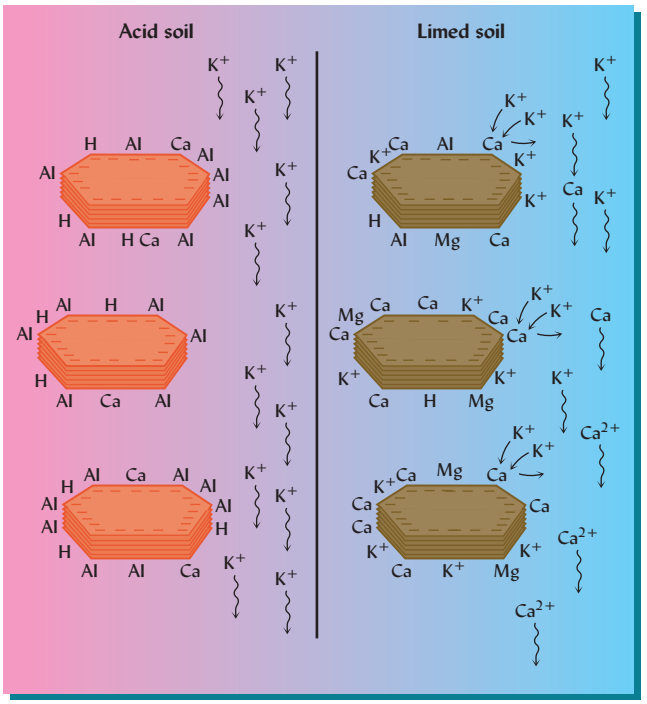

Figure 14.42 *Diagrammatic illustration of how liming an acid soil can reduce leaching losses of potassium. The fact that the K^+ ions can more easily replace Ca^{2+} ions than they could replace Al^{3+} ions allows more of the K^+ ions to be removed from solution by cation exchange in the limed (high-calcium) soil. The removal of K^+ ions from solution by adsorption on the colloids will reduce their loss by leaching, but they will still be at least moderately available for plant uptake.* (Diagram courtesy of Ray R. Weil)

[11]Many of the principles discussed in this section have been studied extensively in the scientific literature, but have sometimes been ignored or downplayed in favor of greater-than-necessary use of "potash" fertilizer (Khan et al., 2014).

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among different elements. Typically, trivalent ions (Al^{3+}) are more tightly held than divalent ions (Ca^{2+} and Mg^{2+}). In a limed soil, where higher levels of exchangeable calcium and magnesium are present, monovalent potassium ions are better able to replace them on the exchange complex. Where higher levels of exchangeable aluminum saturate the exchange complex, potassium is less likely to be adsorbed. Thus, in a limed soil, K^+ can be more readily retained on the exchange complex, and leaching of this element is reduced.

Plant Uptake and Removal

Plants take up very large amounts of potassium, often five to ten times as much as they do phosphorus and about the same amount as for nitrogen. If most or all of the aboveground plant parts are removed in harvest, the drain on the soil supply of potassium can be very large. For example, a 60-Mg/ha yield of corn silage may remove 160 kg/ha of potassium. Conventional bolewood timber harvest typically removes about 100 kg/ha of potassium. If the entire tree is chipped and removed, as for paper pulp, the removal of potassium may be twice as great. Harvest of high-yielding legume hay may remove 400 kg/ha of potassium each year. While these removals are large relative to the exchangeable potassium supply of soils, they are miniscule in relation to the total supply of potassium that is potentially in equilibrium over time with the exchangeable pool.

Luxury Consumption

Uptake and removal of potassium can be exaggerated by the tendency of plants to take up much more potassium than they need if sufficiently large quantities of easily available potassium are present. This tendency is termed *luxury consumption*, because the excess potassium absorbed does not increase plant growth or function. For example, spinach grown after a brassica cover crop on a micaceous soil has been known to accumulate potassium up to 11% of the leaf dry matter.

The principles involved in luxury consumption are shown in Figure 14.43. For many plants there is a direct relationship between the available potassium (soil plus fertilizer) and the removal of this element by the plants. If plant residues are not returned to the soil, the removal of excess potassium by luxury consumption is decidedly wasteful. In addition, high potassium uptake is likely to depress the uptake of other cations, particularly calcium and magnesium, and may thereby cause nutritional imbalances both in the plants and in animals that consume them. Such potassium-induced calcium and magnesium deficiency is of particular concern in forage crops for dairy cows.

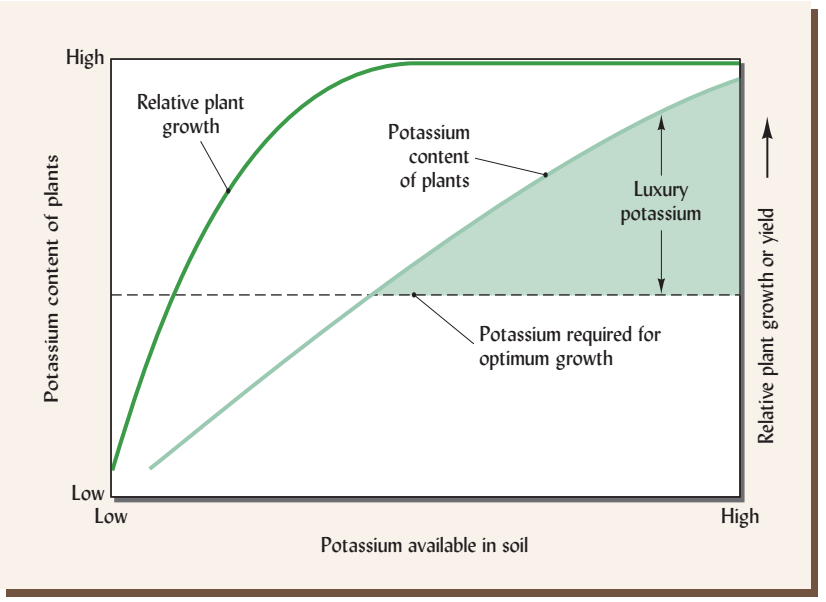

Figure 14.43 *The general relationship between available potassium level in soil, plant growth, and plant uptake of potassium. If available soil potassium is raised above the level needed for maximum plant growth, many plants will continue to increase their uptake of potassium without any corresponding increase in growth. The potassium taken up in excess of that needed for optimum growth is termed* luxury consumption. *Such luxury consumption may be wasteful, especially if the plants are completely removed from the soil. It may also cause dietary imbalance in grazing animals.* (Diagram courtesy of Ray R. Weil)

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In summary, then, the potassium situation in soils is characterized by: (1) a very large total supply throughout the soil profile; (2) a vastly smaller supply that is available to plants in the short term; (3) a susceptibility to substantial leaching losses; and (4) a high rate of removal in harvested agroecosystems, especially when luxury quantities of this element are supplied and consumed. With these ideas as a background, the various forms and availabilities of potassium in soils will now be considered.

14.14 FORMS AND AVAILABILITY OF POTASSIUM IN SOILS

Four forms of soil potassium are shown in the potassium cycle diagram (Figure 14.40, from the bottom upward): (1) K in primary mineral crystal structures, (2) K in nonexchangeable positions in secondary minerals, (3) K in exchangeable form on soil colloid surfaces, and (4) potassium ions soluble in water. The total amount of potassium in a soil and the distribution of potassium among the four major pools shown in Figure 14.40 is largely a function of the kinds of clay minerals present in a soil. Generally, soils dominated by 2:1 clays contain the most potassium; those dominated by kaolinite contain the least (Table 14.8). In terms of availability for plant uptake, the following interpretation applies to the different forms of soil potassium:

K in primary minerals	*Unavailable to very slowly available*
Nonexchangeable **K** in secondary minerals	*Slowly available*
Exchangeable **K** on soil colloids **K** soluble in water	*Readily available*

All plants can easily utilize the readily available forms, but the ability to obtain potassium held in the slowly available and unavailable forms differs greatly among plant species. Many grass plants with fine, fibrous root systems are able to exploit potassium held in clay interlayers and near the edges of mica and feldspar crystals of clay and silt size. A few plants adapted to low-fertility sandy soils, such as elephant grass (*Pennisetum purpureum* Schum.), have been shown to obtain potassium from even sand-sized primary minerals, a form of potassium usually considered to be unavailable.

Relatively Unavailable Forms

Some 90–98% of all soil potassium in a mineral soil occurs in relatively unavailable forms (see Figure 14.40), mostly in the crystal structure of feldspars and micas. These minerals are quite resistant to weathering and supply relatively small quantities of potassium during a given growing season. However, their cumulative release of potassium in the entire soil rooting zone

Table 14.8
THE INFLUENCE OF DOMINANT CLAY MINERALS ON THE AMOUNTS OF WATER-SOLUBLE, EXCHANGEABLE, FIXED (NONEXCHANGEABLE), AND TOTAL POTASSIUM IN SOILS
The values given are means for many soils in ten soil orders sampled in the United States.

	Dominant clay mineralogy of soils, mg K/kg soil		
Potassium pool	**Kaolinitic (26 soils)**	**Mixed (53 soils)**	**Smectitic (23 soils)**
Total potassium	3340	8920	15780
Exchangeable potassium	45	224	183
Water-soluble potassium	2	5	4

Data from Sharpley (1990).

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and over a period of years undoubtedly is of importance. This release is enhanced by the solvent action of carbonic acid and of stronger organic and inorganic acids, as well as by the presence of acidic clays and organic colloids (see Section 2.1). As already mentioned, the roots of some plants can obtain a significant portion of their potassium supply from these minerals, apparently by depleting the potassium ions from the solution around the edges of these minerals, thereby favoring the dissolution of the mineral.

Readily Available Forms

Only 1–2% of the total soil potassium is readily available. Readily available potassium exists in soils in two forms: (1) in the soil solution, and (2) exchangeable potassium adsorbed on the soil colloidal surfaces. Although most of this available potassium (approximately 90%) is in the exchangeable form, soil solution potassium is most readily absorbed by higher plants (but is also subject to considerable leaching loss).

As represented in Figure 14.40, these two forms of readily available potassium are in dynamic equilibrium. This equilibrium is of great practical importance. When plants absorb potassium from the soil solution, some of the exchangeable potassium immediately moves into the soil solution until the equilibrium is again established. When water-soluble fertilizers are added, the soil solution becomes potassium enriched and the reverse adjustment occurs—potassium from soil solution moves onto the exchange complex. The exchangeable potassium thus *buffers* (stabilizes) the concentration of potassium in the soil solution.

Slowly Available Forms

Soil clays composed of vermiculite, smectite, and certain other 2:1-type minerals not only attract and adsorb K^+ ions from the soil solution (including those added as fertilizers) in exchangeable form, but may also *fix* some of the K^+ ions in tightly held, nonexchangeable form (Figure 14.44). Potassium (as well as the similar sized NH_4^+ ions) ions fit in between layers in the crystals of these normally expanding clays and become an integral part of the crystal. These ions cannot be replaced by ordinary exchange processes and consequently are referred to as *nonexchangeable ions.* As such, these ions are not readily available to most plants. This form is in equilibrium, however, with the more available forms and consequently acts as an extremely important reservoir of slowly available nutrients (Figure 14.45).

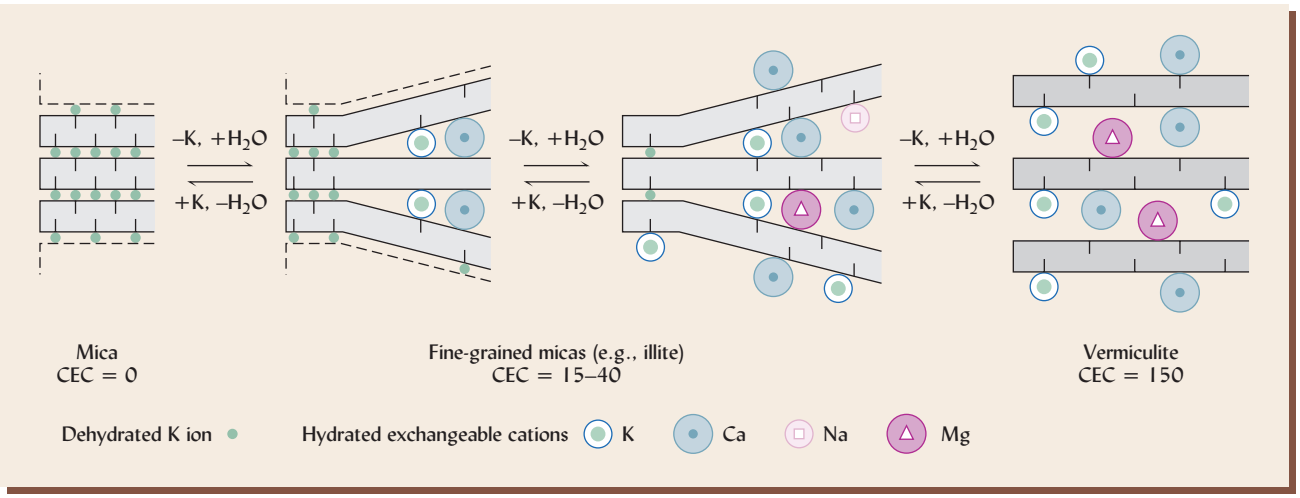

Figure 14.44 *Diagrammatic illustration of the release and fixation of potassium between primary micas, fine-grained mica (illite clay), and vermiculite. In the diagram, the release of potassium proceeds to the right, while the fixation process proceeds to the left. Note that the dehydrated potassium ion is much smaller than the hydrated ions of Na^+, Ca^{2+}, Mg^{2+}, etc. Thus, when potassium is added to a soil containing 2:1-type minerals such as vermiculite, the reaction may go to the left and potassium ions will be tightly held (fixed) in between layers within the crystal, producing a fine-grained mica structure. Ammonium ions (NH_4^+, not shown) are of a similar size and charge to potassium ions and may be fixed by similar reactions.* [Modified from McLean (1978)]

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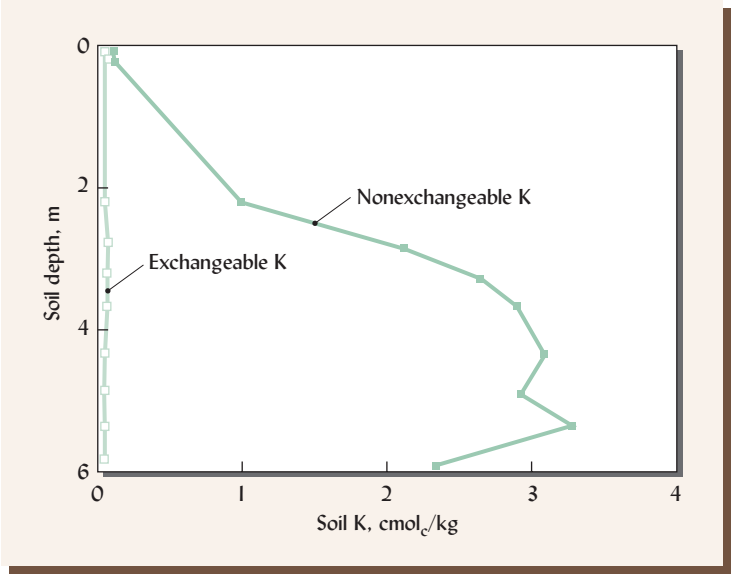

Figure 14.45 *Exchangeable and nonexchangeable potassium levels in an Ultisol in South Carolina, USA, after 30 years growth of a loblolly pine following 150 years of cultivated crops. Although the exchangeable potassium level was quite low, tree growth was not adversely affected, and large quantities of this element were absorbed by the trees over the 30-year period. This was made possible by the conversion of nonexchangeable potassium to the exchangeable form, which was readily taken up by the trees. The upper horizons may have been depleted somewhat of nonexchangeable K, but the deep tree roots were able to use the potassium released from the nonexchangeable form in the lower horizons.* [From Richter et al. (1994)]

Release of Fixed Potassium

The quantity of nonexchangeable or fixed potassium in some soils is quite large. The fixed potassium in such soils is continually released to the exchangeable form in amounts large enough to important for plant nutrition. The data in Table 14.9 indicate the magnitude of the release of nonexchangeable potassium from certain soils. In these soils, the potassium removed by plants was supplied largely from nonexchangeable forms. The entire equilibrium may be represented for potassium as follows:

$$\text{Nonexchangeable K} \overset{\text{Slow}}{\rightleftharpoons} \text{Exchangeable K} \overset{\text{Rapid}}{\rightleftharpoons} \text{Soil solution K} \tag{14.7}$$

As a result of these relationships, very sandy soils with low cation exchange capacity (CEC) are poorly buffered with respect to potassium. In them, the potassium ion concentration may be quite high at the beginning of a growing season or just after fertilization, but these soils have little capacity to maintain the potassium concentration as plants remove the

Table 14.9
POTASSIUM REMOVAL BY INTENSIVE CROPPING AND THE AMOUNT OF THIS ELEMENT COMING FROM THE NONEXCHANGEABLE FORM

Soil	Total K used by crops, kg/ha	Percent derived from nonexchangeable form
Wisconsin soils[a]		
Carrington silt loam	133	75
Spencer silt loam	66	80
Plainfield sand	99	25
Mississippi soils[b]		
Robinsonville fine silt loam	121	33
Houston clay	64	47
Ruston sandy loam	47	24

[a]Average of six consecutive cuttings of ladino clover. [From Evans and Attoe (1948)]
[b]Average of eight consecutive crops of millet. [From Gholston and Hoover (1948)]

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dissolved potassium from the soil solution during the growing season. Late-season potassium deficiency may result. In finer-textured soils with a greater CEC (and therefore greater buffering capacity), the initial solution concentration of potassium may be somewhat lower, but the soil is capable of maintaining a fairly constant supply of solution potassium ions throughout the growing season.

14.15 FACTORS AFFECTING POTASSIUM FIXATION IN SOILS

Five soil conditions markedly influence the amounts of potassium fixed: (1) the nature of the soil colloids, (2) the levels of previous potassium additions and removals, (3) wetting and drying, (4) freezing and thawing, and (5) the presence of excess lime.

Effects of Type of Clay and Moisture

The various soil colloids vary widely in their ability to fix potassium. Kaolinite and other 1:1-type clays fix little potassium. On the other hand, clays of the 2:1 type, such as vermiculite, fine-grained mica (illite), and smectite, fix potassium very readily and in large quantities (Figure 14.46). Even silt-sized fractions of some micaceous minerals fix and subsequently release potassium (Table 14.10).

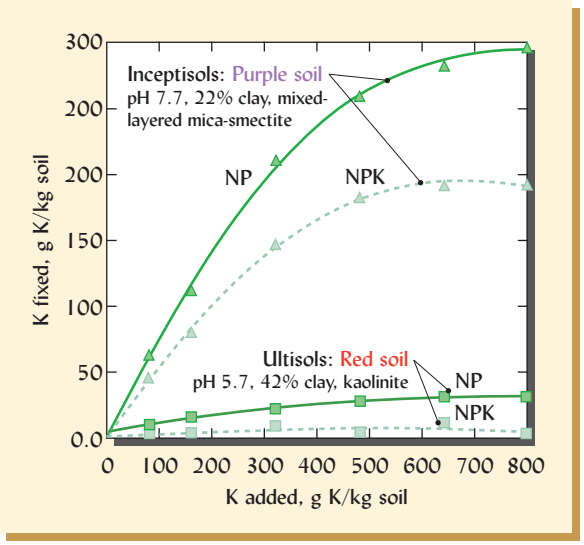

Figure 14.46 *Potassium fixation by two contrasting soils in China subjected to 15 years of cropping and fertilization with (NPK) or without (NP) the annual application of 100 kg/ha of K. The Inceptisol (known as a Purple soil in China) with mixed 2:1 clay mineralogy and an alkaline pH exhibited a much higher K fixation capacity than the Ultisol (known as a Red soil in China) with kaolinitic clays. In both soils the K fixation capacity was considerably reduced by repeated application of K fertilizers. In all cases, N and P fertilizers were applied.* [Recalculated and graphed from selected data in Zhang et al. (2009)]

Table 14.10
UPTAKE OF POTASSIUM BY ROOTS OF RYEGRASS GROWN ON 14 HIGH MICA ALFISOLS WITH AND WITHOUT THE CLAY REMOVED
The mica in the silt and sand fractions provided about 2/3 as much potassium as did the whole soils. The silt fraction was a major source of potassium in these soils.

	K uptake by ryegrass root, mg/pot		
	First harvest	Second harvest	Total
Whole soils	103.2	41.3	144.5
Silt + sand fraction	73.9	23.7	97.6

Calculated from Mengel and Rahmatullah Dou (1998)

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The potassium and ammonium ions are attracted between layers in the negatively charged clay crystals. The tendency for fixation is greatest in minerals where the major source of negative charge is in the silica (tetrahedral) sheet (see Figures 8.13 and 8.16). Consequently, vermiculite has a greater fixing capacity than montmorillonite.

Alternate wetting/drying and freezing/thawing enhance both the fixation of potassium in nonexchangeable forms and the release of previously fixed potassium to the soil solution. Although its mechanism is not well understood, it results in marked seasonal variation in the amounts of exchangeable potassium available for plant uptake.

Influence of pH

Applications of lime sometimes increase potassium fixation. In strongly acid soils the tightly held H^+ and hydroxy aluminum ions prevent the potassium ions from being closely associated with the colloidal surfaces, thus reducing their susceptibility to fixation. As lime increases the pH, the H^+ and hydroxyl aluminum ions are removed or neutralized, making it easier for potassium ions to move closer to the colloidal surfaces, where they are more susceptible to fixation in 2:1 clays.

Furthermore, high calcium and magnesium levels in the soil solution may reduce potassium uptake by the plant because cations tend to compete against one another for uptake by roots. Since the absorption of the potassium ion by plant roots is affected by the activity of other ions in the soil solution, some authorities prefer to use the ratio

$$\frac{[K^+]}{\sqrt{[Ca^{2+}] + [Mg^{2+}]}}$$

rather than the potassium concentration to indicate the available potassium level in solution. Finally, potassium deficiency frequently occurs in calcareous soils even when the amount of exchangeable potassium present would be adequate for plant nutrition on other soils. Potassium fixation as well as cation ratios may be responsible for these adverse effects on calcium carbonate-rich soil.

14.16 PRACTICAL ASPECTS OF POTASSIUM MANAGEMENT

Except in very sandy or highly weathered (Oxisols) or organic (Histisols) soils, the problem of potassium fertility is rarely one of total supply, but rather one of adequate *rate* of transformation from nonavailable to available forms. Where little plant material is removed (e.g., in forests, pastures, rangeland, and some turfgrass), cycling between plant and soil may be adequate for continued plant growth. However, where large amounts of plant material are removed, especially if little plant residue is returned, then the plant–soil cycle may need to be supplemented by release of potassium from less available mineral forms and, in some cases, by fertilization (Figure 14.47).

Vigorous growth of high-potassium-content plants places great demands on the soil supply of available potassium. Moreover, the rate of potassium uptake is not constant, but varies with plant growth stage and season. If high yields of forage legumes such as alfalfa are to be produced, the soil may have to be capable of supplying potassium for very high uptake rates during certain periods, resulting in the need for high levels of fertilization even on soils well supplied with weatherable minerals. However, excessive levels of potassium that depress calcium and magnesium in the forage must be avoided to maintain plant and animal health (see grass tetany, Section 15.2).

Frequency of Application

Although a heavy dressing applied every few years may be most convenient, more frequent light applications of potassium may offer the advantages of reduced luxury consumption, reduced losses by leaching, and reduced opportunity for fixation in unavailable forms before plants have had a chance to use the potassium applied. Although such fixation has definite

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Figure 14.47 *Potassium plays a major role in the competition between grasses and legumes in mixed vegetation. Both photos are from a hayfield established on a micaceous Maryland, USA, silt loam soil as a clover/grass mixture that provided balanced energy and protein for animals. Parts of the field were fertilized annually with 150 kg K/ha and the other parts were not. After ten years of removing hay from the field, the potassium-fertilized parts* (right) *still had an even mixture of grass and legumes. However, in the unfertilized parts* (left)*, the grass outcompeted the legumes for the limited potassium supplies and the legumes soon died out, leaving only grasses.* (Photos courtesy of Ray R. Weil)

conserving features, in most cases these tend to be outweighed by the disadvantages of leaching and luxury consumption associated with large potassium applications.

Potassium-Supplying Power of Soils

Full advantage should be taken of the potassium-supplying power of soils. It is not generally necessary to replace with fertilizers each kilogram of potassium removed by plants or through leaching. In many soils, the large quantities of moderately available forms already present can be utilized so that only a part of the total amount removed by harvest need be replaced by fertilizer. Moreover, the importance of lime in reducing leaching losses of potassium should not be overlooked as a means of effectively utilizing the power of soils to furnish this element.

Soils of arid regions are often well supplied with weatherable potassium-containing minerals and can therefore supply adequate potassium for many years, even under irrigation where leaching is more important and plant removal is great. However, continued crop removal can deplete the available potassium pools even in these soils. Also, deep-rooted plants such as cotton and fruit trees may depend on exchangeable and nonexchangeable potassium in deep soil layers for much of their needs.

Potassium Losses and Gains

The problem of maintaining soil potassium is diagrammed in Figure 14.48. Plant removal of potassium generally exceeds that of the other essential elements, with the possible exception of nitrogen. Annual losses from plant removal as great as 400 kg/ha or more of potassium are not uncommon, particularly if the plant is a legume and is cut several times for hay. As might be expected, therefore, the return of plant residues and manures is very important in maintaining soil potassium.

The annual losses of available potassium by leaching and erosion greatly exceed those of nitrogen and phosphorus. They are generally not as great, however, as the corresponding losses of available calcium and magnesium. Such losses of soil minerals have serious implications for sustainable soil productivity.

Use of Potassium Fertilizers

Because of the large potassium-supplying power of most soils, economically viable responses to potassium fertilization are actually quite rare and there exists little justification for the traditional viewpoint that potassium fertilizer should generally be applied to most soils as part of a

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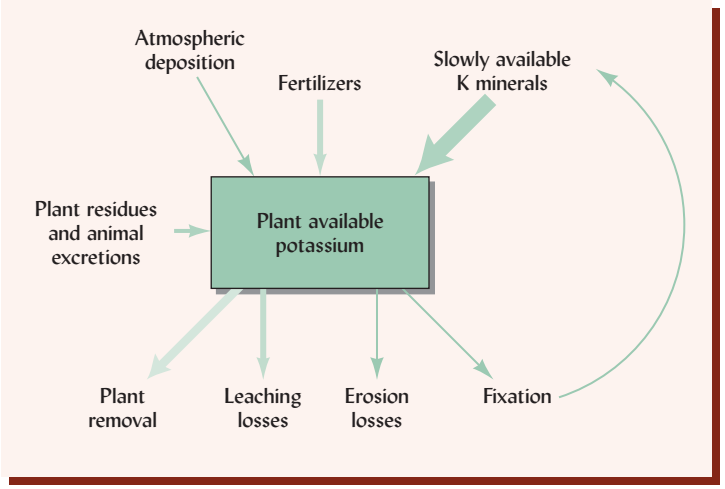

Figure 14.48 *Gains and losses (fluxes) of* available *soil potassium under typical field conditions. The approximate magnitude each flux is represented by the width of the arrow. For any specific case, the actual amounts of potassium added or lost undoubtedly may vary considerably from this representation. In contrast to the cases of nitrogen and phosphorus, commercial fertilizers have a limited role to play in most soils, even where intensive agriculture is practiced.*

"complete" fertilization program. Most cases in which potassium fertilizers have been shown to increase yield or quality of crops have occurred on soils with inherently low potassium-supplying power, namely, very sandy, highly organic, or highly weathered soils. Potassium fertilizers may also be called for where very large amounts of high potassium plant material are removed and/or the depth of plant rooting is very shallow so subsoil contributions to potassium nutrition are minimized.

In most developed and emerging economy countries with established fertilizer industries and marketing schemes, potassium fertilizers, especially KCl, have been over applied and their use can often be reduced. For example, farmers in the United States corn belt increased their use of potassium fertilizer for several decades preceding the 1980s, by which time the potassium-supplying power had been built up to the point that only small, if any, maintenance additions were needed. Such maintenance additions, if needed, can usually be only a fraction of the average potassium removals (the other part of removals being replaced by potassium released by mineral weathering).

However, in certain regions with soils of inherently low potassium-supplying power and a history of negative potassium balances (removals exceeding additions), the pools of available soil potassium have been depleted and increasing crop yields are placing demands on the soil that cannot be met by mineral weathering alone. This is especially true where high potassium use crops are grown on sandy soils or highly weathered soils. In less developed agricultural regions of the world where such soils predominate and fertilizer use has been extremely low to nonexistent, increases in potassium fertilizer use will be needed for some years to come if yields are to be increased or even maintained.

14.17 CONCLUSION

Soil phosphorus presents us with a double-edged sword; its effective management is crucially important from both an environmental standpoint and for soil fertility. On one hand, too little phosphorus commonly limits the productivity of natural and cultivated plants and is the cause of widespread soil and environmental degradation. On the other hand, industrialized agriculture has concentrated too much phosphorus in some cases, resulting in losses from soil that cause egregious eutrophication in surface waters. Some of these situations have been caused by excessive buildup of soil phosphorus with fertilizer. Others are the result of concentration of animal production, so that phosphorus in the manure produced at many livestock facilities far exceeds that required by the crops grown on the surrounding land.

Except in cases of extreme buildup, the availability of phosphorus to plant roots has a double constraint: the low total phosphorus level in soils and the small percentage of this level that is present in available forms. Furthermore, even when soluble phosphates are added

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to soils, they are quickly fixed into insoluble forms that in time become quite unavailable to growing plants. In acid soils, the phosphorus is fixed primarily by iron, aluminum, and manganese; in alkaline soils, by calcium and magnesium. This fixation greatly reduces the efficiency of phosphate fertilizers, with little of the added phosphorus being taken up by plants. In time, however, this unused phosphorus can build up and serve as a reserve pool for plant absorption.

Potassium is generally abundant in soils, but it, too, is present mostly in forms that are relatively unavailable for plant absorption. Fortunately, however, most soils contain considerable nonexchangeable but slowly available forms of this element. Over time this potassium can be released to exchangeable and soil solution forms that can be quickly absorbed by plant roots. This is fortunate since the plant requirements for potassium are high—5–10 times that of phosphorus and similar to that of nitrogen.

Finally, in studying the use and management of these mineral nutrients, it is important to keep in mind the sobering truth that, although accessible potassium supplies are quite large, the world's supply of useable phosphorus is predicted to become exhausted within a century or so, if today's wasteful practices continue. While substitutes can be found for many finite natural resources mined from the Earth—copper in phone lines can be replaced by fiber optics, steel in car bodies by composite plastics, and petroleum in transportation fuels by biodiesel or hydrogen cells—this is *not* the case for phosphorus in food production. The U.S. Geological Survey[12] lists the following under the heading *Substitutes for Phosphate Rock*: "THERE ARE NO SUBSTITUTES FOR PHOSPHORUS . . . "

[12]Jasinski (2013).

STUDY QUESTIONS

1. You have learned that nitrogen, potassium, and phosphorus are all "fixed" in the soil. Compare the processes of these fixations and the benefits and constraints they each provide.
2. Assume you add a soluble phosphate fertilizer to an Oxisol and to an Aridisol. In each case, within a few months most of the phosphorus has been changed to insoluble forms. Indicate what these forms are and the respective compounds in each soil responsible for their formation.
3. How does the phosphorus content of cultivated soils in the United States compare with that of nearby soils under natural vegetation (forests, grasslands) that have never been cleared? What is the reason for this difference?
4. What is meant by *eutrophication*, and how is it influenced by farm practices involving phosphorus?
5. Which is likely to have the higher buffering capacity for phosphorus and potassium, a loamy sand or a clay soil? Explain.
6. In the spring a certain surface soil showed the following soil test: soil solution K = 20 kg/ha; exchangeable K = 200 kg/ha. After two crops of alfalfa hay that contained 250 kg/ha of potassium were harvested and removed, a second soil test showed soil solution K = 15 kg/ha and exchangeable K = 200 kg/ha. Explain why there was not a greater reduction in soil solution and exchangeable K levels.
7. What is the effect of soil pH on the availability of phosphorus, and what are the unavailable forms at the different pH levels?
8. What is *luxury consumption* of plant nutrients, and what are its advantages and disadvantages?
9. How does phosphorus that forms relatively insoluble inorganic compounds in soils find its way into streams and other waterways?
10. The incorporation of large amounts of wheat straw into a soil may bring about P deficiency in the following crop. What is the likely reason for this?
11. The incorporation of large amount of wheat straw is very *un*likely to bring about a deficiency of K in the following crop. Explain at least two reasons why this is so.
12. Compare the organic P levels in the upper horizons of a forested soil with those of a nearby soil that has been cultivated for 25 years. Explain the difference.
13. For establishment of new turf in a golf fairway, the recommendations from soil testing call for the application of 2000 kg of limestone powder, 200 kg of triple super phosphate fertilizer, and 200 kg of urea fertilizer. The materials are to be incorporated by raking into the upper 4 cm of soil. The superintendent suggests that all three materials be mixed together and then applied in a single operation to save time and money. Is this a good or bad idea? Give a detailed explanation based on chemistry.
14. Overapplication of any nutrient resource is to be avoided. Explain the different negative consequences resulting from overapplication of P as compared to overapplication of K.

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REFERENCES

Baker, L. A. 2011. "Can urban P conservation help to prevent the brown devolution?" *Chemosphere* **84**:779–784.

Batterman, S. A., N. Wurzburger, and L. O. Hedin. 2013. "Nitrogen and phosphorus interact to control tropical symbiotic N_2 fixation: A test in Inga punctata." *Journal of Ecology* **101**:1400–1408.

Bittman, S., C. G. Kowalenko, D. E. Hunt, T. A. Forge, and X. Wu. 2006. "Starter phosphorus and broadcast nutrients on corn with contrasting colonization by mycorrhizae." *Agronomy Journal* **98**:394–401.

Brady, N. C. 1974. *The Nature and Properties of Soils*, 8th ed. Macmillan, New York.

Buresh, R. J., P. C. Smithson, and D. T. Hellums. 1997. "Building soil phosphorus capital in Africa." In R. J. Buresh, P. A. Sanchez, and F. Calhoun (eds.). *Replenishing Soil Fertility in Africa*. SSSA Special Publication No. 51. Soil Science Society of America, Madison, WI.

Butusov, M., and A. Jernelöv. 2013. *Phosphorus: An Element that could have been called Lucifer*. Springer, New York, p. 101.

Cogger, C., and J. M. Duxbury. 1984. "Factors affecting phosphorus loss from cultivated organic soils." *Journal of Environmental Quality* **13**:111–114.

Cordell, D., and S. White. 2015. "Tracking phosphorus security: Indicators of phosphorus vulnerability in the global food system." *Food Security* 7:337–350.

Devau, N., E. L. Cadre, P. Hinsinger, B. Jaillard, and F. Gérard. 2009. "Soil pH controls the environmental availability of phosphorus: Experimental and mechanistic modelling approaches." *Applied Geochemistry* **24**:2163–2174.

Dodd, R.J., and A.N. Sharpley. 2015. "Recognizing the role of soil organic phosphorus in soil fertility and water quality." *Resources, Conservation and Recycling* 105 part B:282–293.

Eghball, B., G. D. Binford, and D. D. Baltensperger. 1996. "Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application." *Journal of Environmental Quality* **25**:1339–1343.

Emsley, J. 2002. *The 13th Element: The Sordid Tale of Murder, Fire, and Phosphorus*. John Wiley & Sons, New York, p. 352.

Evans, C. E., and O. J. Attoe. 1948. "Potassium supplying power of virgin and cropped soils." *Soil Science* **66**:323–334.

FAO. 2014. Faostat [Online]. Food and Agriculture Organization of the United Nations. Available at http://faostat.fao.org/ (verified 20 May 2014).

Fares, F., J. C. Fardeau, and F. Jacquin, 1974. "Quantitative survey of organic phosphorus in different soil types." *Phosphorus and Agriculture* **63**:25–41.

Fox, R. L. 1981. "External phosphorus requirements of crops." *Chemistry in the Soil Environment*. ASA Special Publication No. 40. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 223–239.

Frossard, E., L. M. Condron, A. Oberson, S. Sinaj, and J. C. Fardeau. 2000. "Processes governing phosphorus availability in temperate soils." *Journal of Environmental Quality* **29**:15–23.

Garrison-Johnston, M.T., T.M. Shaw, P.G. Mika, and L.R. Johnson. 2005. "Management of ponderosa pine nutrition through fertilization." Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management. October 18–21, 2004, Klamath Falls, Oregon. US Forest Service. 123–143. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.154.778&rep=rep1&type=pdf#page=167

Gholston, L. E., and C. D. Hoover. 1948. "The release of exchangeable and nonexchangeable potassium from several Mississippi and Alabama soils upon continuous cropping." *Soil Science Society of America Proceedings* **13**:116–121.

Goenadi, D. H., Siswanto, and Y. Sugiarto. 2000. "Bioactivation of poorly soluble phosphate rocks with a phosphorus-solubilizing fungus." *Soil Science Society of America Journal* **64**:927–932.

Jasinski, S. M. 2013. "Phosphate rock." U.S. Department of the Interior, U.S. Geological Survey, Reston, VA. http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2013-phosp.pdf.

Khan, S. A., R. L. Mulvaney, and T. R. Ellsworth. 2014. "The potassium paradox: Implications for soil fertility, crop production and human health." *Renewable Agriculture and Food Systems* **29**:3–27.

Koele, N., T. W. Kuyper1, and P. S. Bindraban. 2014. "Beneficial organisms for nutrient uptake." VFRC Report 2014/1. Virtual Fertilizer Research Center, Washington, D.C. http://www.vfrc.org.

Kuo, S. 1988. "Application of modified Langmuir isotherm to phosphate sorption by some acid soils." *Soil Science Society of America Journal* **52**:97–102.

Li, L., S.-M. Li, J.-H. Sun, L.-L. Zhou, X.-G. Bao, H.-G. Zhang, and F.-S. Zhang. 2007. "Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils." *Proceedings of the National Academy of Sciences* **104**:11192–11196.

Liu, J., R. Khalaf, B. Ulén, and G. Bergkvist. 2013. "Potential phosphorus release from catch crop shoots and roots after freezing-thawing." *Plant and Soil* **371**:543–557.

Mamo, M., and C. Wortmann. 2009. "Phosphorus sorption as affected by soil properties and termite activity in eastern and southern Africa." *Soil Science Society of America Journal* **73**:2170–2176.

McLean, E. O. 1978. "Influence of clay content and clay composition on potassium availability." In G. S. Sekhon

FOR REFERENCE PURPOSES ONLY

(ed.). *Potassium in Soils and Crops*. Potash Research Institute of India, New Delhi, pp. 1–19.

Mengel, K., and E. A. Kirkby. 2001. *Principles of Plant Nutrition*, 5th ed. Kluwer Academic Publishers, Dordrecht, Netherlands.

Mengel, K., and H. Rahmatullah Dou. 1998. "Release of potassium from the silt and sand fractions of loess-derived soils." *Soil Science* **163**:805–813.

Miller, W. W., D. W. Johnson, T. M. Loupe, J. S. Sedinger, E. M. Carroll, J. D. Murphy, R. F. Walker, and D. Glass. 2006. "Nutrients flow from runoff at burned forest site in Lake Tahoe basin." *California Agriculture* **60**:65–71.

Nair, K. P. P. 1996. "The buffering power of plant nutrients and effects on availability." *Advances in Agronomy* **57**:237–287.

Nair, V. D., A. A. Graetz, and K. M. Portier. 1995. "Forms of phosphorus in soil profiles from dairies of South Florida." *Soil Science Society of America Journal* **59**:1244–1249.

Nowak, C. A., R. B. Downard, Jr., and E. H. White. 1991. "Potassium trends in red pine plantations at Pack Forest, New York." *Soil Science Society of America Journal* **55**:847–850.

Obersteiner, M., J. Peñuelas, P. Ciais, M. van der Velde, and I. A. Janssens. 2013. "The phosphorus trilemma." *Nature Geoscience* **6**:897–898.

Ohio Lake Erie Phosphorus Task Force. 2013. "Ohio Lake Erie Phosphorus Task Force 2." Final Report. Ohio Departments of Agriculture and Natural Resources, Environmental Protection Agency and Lake Erie Commission. http://lakeerie.ohio.gov/Portals/0/Reports/Task_Force_Report_October_2013.pdf.

Raven, K. P., and L. R. Hossner. 1993. "Phosphorus desorption quantity-intensity relationships in soils." *Soil Science Society of America Journal* **57**:1501–1508.

Richter, D. D., D. Markewitz, C. G. Wells, H. L. Allen, R. April, P. R. Heine, and B. Urrego. 1994. "Soil chemical change during three decades in an old-field Loblolly pine (*Pinus taeda L.*) ecosystem." *Ecology* **75**:1463–1473.

Römheld, V., and E. Kirkby. 2010. "Research on potassium in agriculture: Needs and prospects." *Plant and Soil* **335**:155–180.

Sanchez, P. A. 2002. "Soil fertility and hunger in Africa." *Science* **295**:2019–2020.

Scholz, R.W., D.T. Hellums, and A.A. Roy. 2015. Global sustainable phosphorus management: A transdisciplinary venture. *Current Science* 108:1237–1246.

Sharma, S., E. Duveiller, R. Basnet, C. B. Karki, and R. C. Sharma. 2005. "Effect of potash fertilization on Helminthosporium leaf blight severity in wheat, and associated increases in grain yield and kernel weight." *Field Crops Research* **93**:142–150.

Sharpley, A. 2000. "Phosphorus availability." In M. E. Summer (ed.). *Handbook of Soil Science*. CRC Press, New York, pp. D-18–D-38.

Sharpley, A. N. 1990. "Reaction of fertilizer potassium in soils of differing mineralogy." *Soil Science* **49**:44–51.

Sharpley, A., and B. Moyer. 2000. "Phosphorus forms in manure and compost and their release during simulated rainfall." *Journal of Environmental Quality* **29**:1462–1469.

Smit, A. L., M. Blom-Zands, A. v. d. Werf, and P. S. Bindraban. 2013. "Plant strategies and cultural practices to improve the uptake of indigenous soil P and the efficiency of fertilization." VFRC Report 2013/4. Virtual Fertilizer Research Center, Washington, D.C. http://www.vfrc.org.

Smith, S. E., I. Jakobsen, M. Grønlund, and F. A. Smith. 2011. "Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition." *Plant Physiology* **156**:1050–1057.

Smith, S. J., A. N. Sharpley, J. W. Naney, W. A. Berg, and O. R. Jones. 1991. "Water quality impacts associated with wheat culture in the Southern Plains." *Journal of Environmental Quality* **20**:244–249.

Soltanpour, P. N., R. L. Fox, and R. C. Jones. 1988. "A quick method to extract organic phosphorus from soils." *Soil Science Society of America Journal* **51**:255–256.

Sui, Y., and M. L. Thompson. 2000. "Phosphorus sorption, desorption, and buffering capacity in a bio-solids-amended Mollisol." *Soil Science Society of America Journal* **64**:164–169.

Tekalign, M., I. Haque, and C. S. Kamara. 1988. "Phosphorus status of some Ethiopian highland Vertisols." In S. C. Jutzi, I. Haque, J. McIntyre, and J. E. S. Stares (eds.). *Management of Vertisols in Sub-Saharan Africa*. Proceedings of a conference held at the International Livestock Research Center (ILCA), Addis Ababa, Ethiopia, 31 August–4 September 1987. ILCA, Addis Ababa, pp. 232–252.

Torbert, H. A., K. W. King, and R. D. Harmel. 2005. "Impact of soil amendments on reducing phosphorus losses from runoff in sod." *Journal of Environmental Quality* **34**:1415–1421.

Vaithiyanathan, P., and D. L. Correll. 1992. "The Rhode River watershed: Phosphorus distribution and export in forest and agricultural soils." *Journal of Environmental Quality* **21**:280–288.

Weil, R. R., P. W. Benedetto, L. J. Sikora, and V. A. Bandell. 1988. "Influence of tillage practices on phosphorus distribution and forms in three Ultisols." *Agronomy Journal* **80**:503–509.

FOR REFERENCE PURPOSES ONLY

White, C. M., and R. R. Weil 2009. "Forage radish and cereal rye cover crop effects on mycorrhizal fungus colonization of corn roots." *Plant and Soil* **328**:507–521.

White, C. M., and R. R. Weil 2011. "Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes." *Soil Science Society of America Journal* **75**:121–130.

Wyant, K. A., J. E. Corman, J. R. Corman, and J. J. Elser. 2013. "Phosphorus, food, and our future." Oxford University Press, Oxford, UK, p. 224.

Yang, X., W. M. Post, P. E. Thornton, and A. Jain. 2013. "The distribution of soil phosphorus for global biogeochemical modeling." *Biogeosciences* **10**:2525–2537.

Young, E. O., D. S. Ross, B. J. Cade-Menun, and C. W. Liu. 2013. "Phosphorus speciation in riparian soils: A phosphorus-31 nuclear magnetic resonance spectroscopy and enzyme hydrolysis study." *Soil Science Society of America Journal* **77**:1636–1647.

Zhang, H., M. Xu, W. Zhang, and X. He. 2009. "Factors affecting potassium fixation in seven soils under 15-year long-term fertilization." *Chinese Science Bulletin* **54**:1773–1780.

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15 Calcium, Magnesium, Silicon, and Trace Elements

Look and you will find it . . .
what is unsought will go undetected . . .
—*Sophocles*

Mountain goat finds needed trace elements in plants growing on alpine soils. (Ray R. Weil)

Plant nutrition and other ecosystem functions are influenced by a number of chemical elements, in addition to those (C, N, S, P, and K) that were the focus of Chapters 12–14. Calcium, magnesium, and silicon are taken up by plants in large amounts and are major constituents of minerals in most soils. The biogeochemical cycling of each of these elements plays an important role in soil and ecosystem function.

Calcium and magnesium are among the most abundant cations on the exchange complex in most soils and critical roles in counteracting soil and water acidification. As discussed in Chapter 9, these nonacid cations are supplied in various ground limestones used to raise the pH of acid soils; they lower the levels of acid cation saturation and enhance pH buffering. Calcium and magnesium are also essential nutrients for plant, animal, and microbial life. They are especially important in helping plants overcome a wide range of environmental stresses.

Silicon is the second most abundant element in soils, with the exception of some Histosols and Oxisols. Although silicon is not considered a universally essential nutrient, most plants take it up in large amounts and use it in ways that enhance their growth and ability to cope with environmental stress and disease. Many examples of positive crop responses to silicon fertilization have been documented.

Eight elements (iron, manganese, zinc, copper, boron, molybdenum, nickel, and chlorine) are essential nutrients for plant growth, but required in such small quantities that they are called *micronutrients*. This term must not be construed to imply that these nutrients are somehow less important than macronutrients. To the contrary, too little or too much of one or more of the micronutrients can stimulate dramatic effects in terms of competitive shifts in plant species, stunted growth, low yields, dieback, and even plant death. When they are needed, very small applications of micronutrients can produce striking results.

Micronutrient deficiencies are becoming increasingly commonplace in agriculture as a consequence of higher levels of their removal by ever more productive crops, but also as a result of reduced inadvertent application of these elements in fertilizers and organic amendments. Low levels of these elements in food crops can have widespread negative impacts on human health.

Trace element is a more general term used to describe elements present in tissues and other environmental samples in very small concentrations. Trace elements include the micronutrients just mentioned, as well as such elements as cobalt and vanadium, which are not universally essential but can improve the growth of some plant species. Animals,

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including humans, also require most of these elements in their diets. The trace elements selenium, chromium, tin, iodine, and fluorine serve as essential micronutrients for animals but apparently not for plants. Some trace elements, such as arsenic and cadmium, are of environmental interest primarily because of their potentially toxic effects. Levels of trace elements toxic to plants or to animals may result from natural soil conditions, from pollution, or from soil-management practices. Excess levels of certain trace elements can render plants unsafe to eat and can lead to toxic water pollution.

This chapter will provide some of the background and tools needed to recognize and deal effectively with the varied plant deficiencies and toxicities encountered in a wide range of soil–plant systems. Soil contamination by trace elements will be addressed in Chapter 18.

15.1 CALCIUM AS AN ESSENTIAL NUTRIENT[1]

Calcium (Ca) is a macronutrient essential for all plants. The ability of a soil to supply this element is intimately tied to soil acidity because calcium is the main nonacid cation that reduces aluminum saturation and is a major constituent of most liming materials used to raise soil pH (Sections 9.3 and 9.4). The calcium status of soils has a major influence on the species composition and productivity of terrestrial ecosystems. For animals, the calcium content of the plants they eat is important because calcium is a major component of bones and teeth and plays important roles in many physiological processes. Before the application of calcium transformed the region into the thriving center of South America's agricultural economy, the acid soils of the Brazilian Cerrado region were so infertile that the area was considered a wasteland. The soils were so low in calcium that ranchers trying to graze herds on the Cerrado vegetation would lose cattle from broken bones due to calcium deficiency. It has even been suggested that the relatively higher calcium status of soils in Africa compared to those in South America may account for the occurrence of such large herbivores as elephants, zebras, and giraffes in semiarid savannas in Africa but not in South America.

Calcium in Plants

Amounts Taken Up. Plants generally use Ca in amounts second only to nitrogen and potassium; however, the amount of Ca in plant foliage varies widely from as low as 0.1 to as high as 5% of the dry matter. Most grasses and other monocots restrict the passage of Ca into their roots when the concentration of Ca in the soil solution is high, and they are therefore considered to be *calcifuge* (calcium avoiding) plants. These plants grow well with 0.15–0.5% Ca in leaf tissues. Some dicots such as those in the Brassica family are considered to be *calcicoles* (Latin: *chalk dwelling*) and need 1–3% Ca in their leaves for optimal growth. Trees store a great deal of calcium in their woody tissues; the net calcium uptake by many trees is close to that of nitrogen (see Table 16.6).

Physiological Roles. Calcium is a major component of the middle lamella of cell walls, Ca–pectates giving the wall much of its stiffness. Calcium is also intimately involved with cell elongation and division, membrane permeability, and the activation of several critical enzymes. Through its role in maintaining the integrity of the cell membranes, calcium is critical for protecting the cell against toxicities of other elements.

In contrast to most nutrients, calcium is taken up almost exclusively by young root tips whose endodermis cells have not yet matured to the point of becoming impermeable (suberized). Redistribution of calcium within the plant occurs mainly with the transpiration water in the xylem, rather than in the phloem. These two facts account for the restricted movement of calcium to growing tissues that are not drawing water by transpiration (i.e., to fruits rather than to leaves).

Deficiency Symptoms. Since Ca^{2+} is usually the most abundant of the nonacid cations in soils, for most plants deficiencies of calcium are quite rare, except in very acid soils. When

[1]For a review of calcium in soils and plants, see Chapter 11 in Mengel and Kirby (2001). For a brief interview with renowned soil scientist Pedro Sanchez on the change that calcium made in the Cerrado, see Taylor (2005). For a description of long-term calcium depletion in acidified forests, see Johnson et al. (2008).

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calcium deficiency does occur, it is usually associated with growing points (meristems) such as buds, unfolding leaves, fruits, and root tips (Figure 15.1). Foliar symptoms of calcium deficiency are not commonly seen. However, they may occur in extremely acid soils where plants are likely to also suffer from aluminum toxicity and other problems. Under calcium deficiency, the root system is often shorter and denser than normal. When calcium is deficient, normally harmless levels of other metals can become toxic to the plant—including nutrient metals like magnesium, zinc, or manganese, as well as non-nutrient metals such as aluminum. Under such conditions, calcium-deficient roots become severely stunted and gelatinous (Figure 15.2). These root effects can cause sensitive forest trees to lose branches and eventually die. In very acid soils, Ca deficiency is often accompanied by Al or Mn toxicity, and the related effects on plants are difficult to tell apart.

Certain plants show Ca deficiency, even when the soil pH is adequately maintained by liming. Such deficiencies are often related to the transport of Ca within the plant. Blossom-end rot is an exceptionally disheartening example. Imagine a gardener about to pick a delicious-appearing ripe tomato—only to find that the bottom (blossom-end) of the fruit is a soft, black, rotten mass (Figure 15.1*b*). This disorder, especially common in melons and tomatoes, is caused by inadequate Ca for the cell walls of the expanding fruit. It is usually associated with unevenness in the water supply that interrupts the flow of Ca. Similarly, a peanut grower may have healthy-appearing plants, but find that the pods are empty shells (called pops) with no peanut inside. Again, the cause is inadequate Ca transport to the developing seed. The remedy is to supply lime or gypsum directly to the shallow layer of soil in which the pods develop for direct

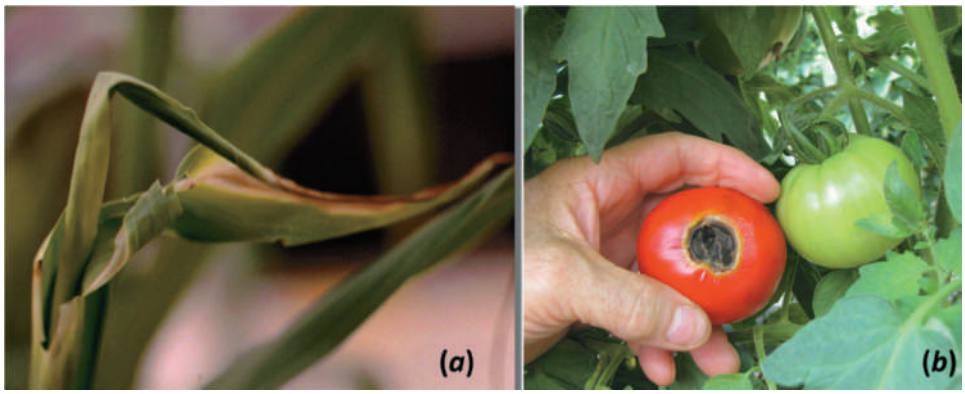

Figure 15.1 *Plant symptoms related to calcium deficiency are commonly expressed on plant parts that are not located along the transpiration stream and therefore least likely to receive calcium. (a) Young leaves that stick together and fail to unfold are a typical symptom of calcium deficiency in monocots. (b) common symptom of calcium deficiency is blossom end rot, caused by inadequate calcium supply to the fruit. Note the black, rotten bottom side of the tomato fruit. The problem may be associated with low calcium translocation due to irregular soil water availability.* (Photos courtesy of Ray R. Weil)

Figure 15.2 *Root growth was almost completely inhibited by lack of calcium in the nutrient solution (left) compared to healthy roots in the same nutrient solution but with calcium added (right). If the molar ratio of calcium to all other cations in solution drops below 5:1, the integrity of root membranes is lost, causing certain other elements to be taken in in toxic amounts.* (Photos courtesy of Ray R. Weil)

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uptake through the shell rather than via the root system located deeper in the soil. Calcium applications, sometimes made directly to the tree foliage, are often required to avoid bitter pit symptoms on apples, which give the fruit brown, corky-textured and bitter-tasting flesh.

Soil Forms and Processes

Forms in Soils. Calcium in the soil is found mainly in three pools that resupply the soil solution: (1) calcium-containing minerals (such as calcite or plagioclase), (2) calcium complexed with soil organic matter, and (3) calcium held by cation exchange on the clay and organic colloids. The cycling of calcium among these and other soil pools, and the gains and losses of calcium by such mechanisms as plant uptake, atmospheric deposition as dust and soot, liming, and leaching, comprise the calcium cycle, as illustrated in Figure 15.3. In most soils, the principal sources supplying Ca to the soil solution for plant uptake are: (1) exchangeable Ca and (2) Ca in readily weathered minerals (such as carbonates and apatite). In arid and semiarid regions, the high pH, high carbonate nature of the soil solution greatly diminishes the solubility of calcium-containing minerals.

Downwind from "dirty" coal-burning industries without effective environmental controls, considerable calcium is deposited in particulate air pollution. Deposition of dust from wind erosion of calcareous desert soils can make substantial contributions to soil calcium thousands of kilometers downwind. Such calcium deposition can partially offset acidification caused by nitrogen and sulfur deposition (see Sections 13.14 and 13.17). Central and southeastern China provide some of the most extreme examples of Ca deposition as environmental policies struggle to keep pace with rapid industrialization. For example, the combination of desert dust and industrial coal burning deposits as much as 120 kg Ca ha^{-1} yr^{-1} on soils near Tie Shan Ping in central China. Yet, with over 200 kg ha^{-1} yr^{-1} of combined nitrogen and sulfur deposition, the deposited calcium succeeds in raising the mean pH of the rain from about 3.0 to only about 4.1, a sizeable shift, but still a very serious acidification problem.

Leaching Losses from Cropland. The need for repeated applications of limestone in humid regions (Section 9.8) suggests significant losses of calcium and magnesium from the soil. Table 15.1 illustrates losses of these elements by leaching compared with those from crop removal and soil erosion. Note that the total loss from all three causes (leaching, erosion, and crop removal) in humid-region agricultural soils, expressed in the form of carbonates, approaches 1 Mg/ha per year. Typical recommendations in humid regions suggest about 1 Mg/ha should be applied every four years to maintain soil pH, once the desired level is achieved. This amount of lime may replace exchangeable Ca lost by leaching, but not that which is lost by crop removal and erosion. Presumably, in most soils the difference is made up by weathering of Ca from minerals.

Losses from Forests. Similarly, timber harvest methods that leave the soil open to erosion and nutrient leaching lead to rapid losses of calcium (and magnesium) from forest ecosystems. Even relatively undisturbed forests in the humid eastern United States may lose calcium by leaching and removal in trees at rates that exceed inputs by atmospheric deposition (Table 15.1). Scientists are concerned that for some soils in the humid regions, the release of Ca from mineral weathering will not be able to keep up with the losses and that acid rain combined with intensive timber harvesting may be depleting the Ca reserves in the more poorly buffered watersheds. The acidification affects a number of biogeochemical processes involving calcium. These processes in turn influence tree physiology, which ultimately impacts the ecological functioning of forests (Table 15.2). Nonetheless, research in this area is still inconclusive and up to now forests have rarely shown a positive growth response to calcium applied as a plant nutrient supplement.

15.2 MAGNESIUM AS A PLANT NUTRIENT

Magnesium in Plants

Roles in Plant. Plants generally take up Mg in amounts (0.15–0.75% of dry matter) similar to or somewhat smaller than they do Ca. About one-fifth of the magnesium in plant tissue is

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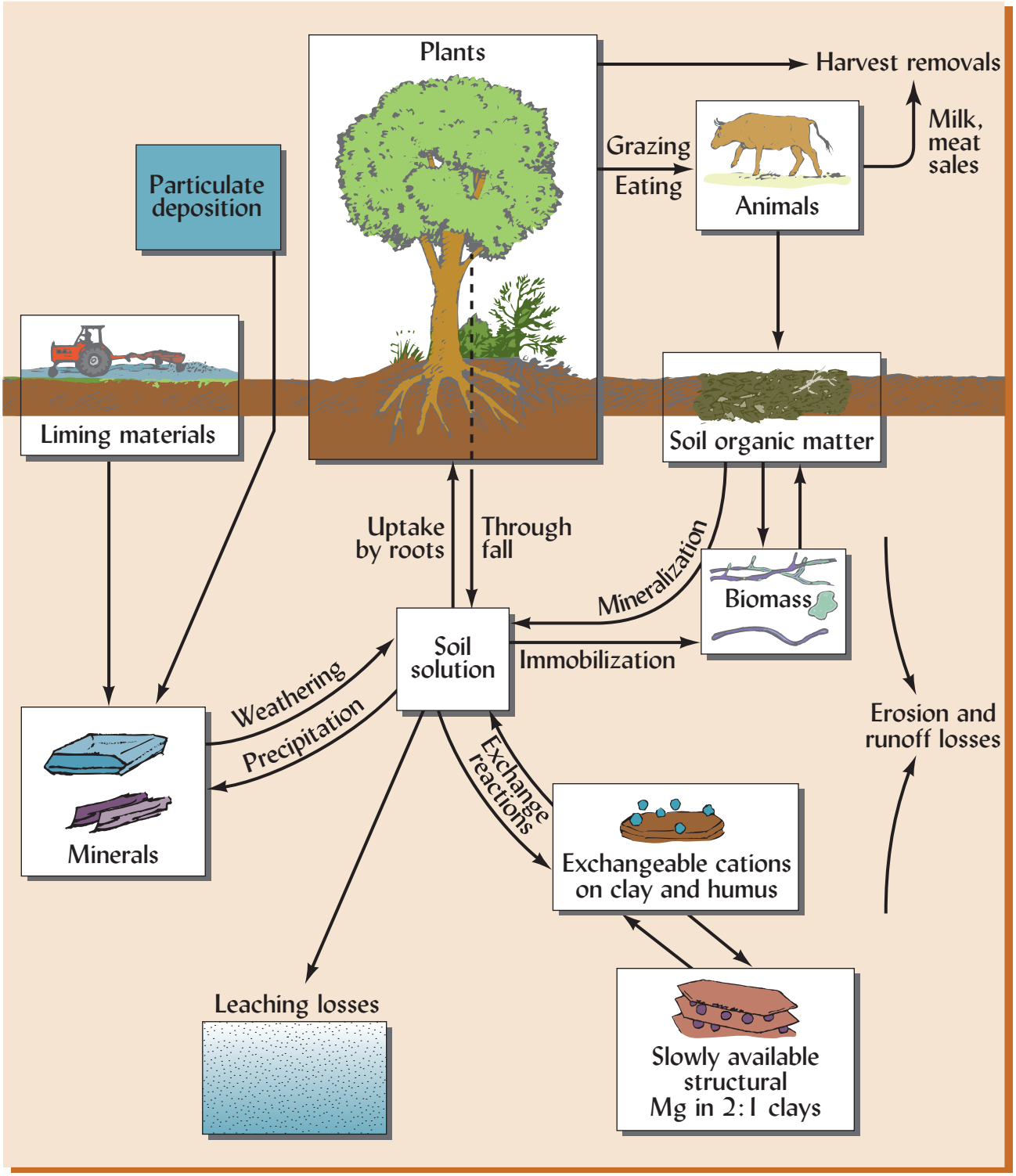

Figure 15.3 *Plant symptoms related to calcium deficiency are commonly Simplified diagram of the cycling of calcium and magnesium in soils. The rectangular compartments represent pools of these elements in various forms, while the arrows represent processes by which the elements are transformed or transported from one pool to another.* (Diagram courtesy of Ray R. Weil)

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Table 15.1
ANNUAL CALCIUM AND MAGNESIUM LOSSES FROM CROPLAND AND FORESTLAND IN HUMID REGIONS
Note that the annual combined loss of Ca and Mg from the cropland was nearly 1 Mg/ha, expressed as carbonates. For the eight eastern U.S. forested watersheds, the average annual input of Ca from atmospheric deposition (6 kg/ha) is enough to approximately offset only the leaching losses of Ca, but not the removal of Ca in timber harvest.

	Loss, kg/ha/yr	
Ecosystem and manner of loss	**Calcium**	**Magnesium**
Cropland in Missouri (silt loam, 4% slope)		
Erosion by water	95	33
Crop removal in standard rotation	50	25
Leaching	115	25
Total from cropland	260 (651 as $CaCO_3$)	83 (291 as $MgCO_3$)
	942 total carbonates	
Apple orchard in New York—leaching losses	170	84
Douglas fir watersheds, loss in streams		
From clear-cut and slash/burned	81	26
From undisturbed watershed	26	8
Average of 4 eastern U.S. mixed hardwood forests		
Net tree removal (uptake-litterfall)	13	NR[a]
Leaching loss in streams	5	NR
Average of 4 catchments in the Black Forest, Germany		
Leaching loss in streams	12	2.4

[a]NR = not reported.
Eastern U.S. forest data calculated from Lawrence and Huntington (1999); apple orchard from Richards et al. (1998); Black Forest from Sommer et al. (2006); others from Brady and Weil (1996).

Table 15.2
CASCADE OF CALCIUM-RELATED EFFECTS FROM ACID DEPOSITION ON FORESTS

Biogeochemical response →	Physiological response →	Effect on forest function
• Leaching of Ca from leaf membrane	• Reduced cold tolerance of needles in red spruce	• Loss of current-year needles in red spruce
• Reduction of the Ca:Al and Ca:Mn ratios in soil and in soil solutions	• Dysfunction in fine roots of red spruce, blocking uptake of Ca	• Decreased growth and increased susceptibility to stress in red spruce
	• Greater energy use to acquire Ca in soils with low Ca:Al ratios	• Decreased growth and increased photosynthate allocation to roots
• Reduction of the availability of nutrient cations in marginal soils	• Sugar maples on drought- prone or nutrient-poor soils are less able to withstand stresses	• Episodic dieback and growth impairment in sugar maple

Modified from Fenn et al. (2006).

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found as the central component of the chlorophyll molecule and so is intimately involved with photosynthesis in plants. Magnesium also plays critical roles in the synthesis of oils and proteins and in the activation of enzymes involved in energy metabolism. The Mg^{2+} ion forms a bridge connecting ATP molecules (which provide energy for cellular reactions, see Section 14.1) to the enzymes that catalyze numerous physiological processes involving phosphorylation.

Deficiency Symptoms. The deficiency of Mg is much more common than that of Ca, at least when the soil pH is at an appropriate level. The most common symptom of Mg deficiency is interveinal chlorosis on the older leaves, which appears as a mottled green and yellow coloring in dicots (Figure 15.4) and a striping in monocots. Because Mg (unlike Ca) is readily translocated in most plants from the older to the younger, still-growing leaves, the oldest leaves are the first to be affected by low Mg supplies. Common on very sandy soils with low cation exchange capacity (CEC), these symptoms are sometimes termed *sand drown* as they appear somewhat like those caused by oxygen starvation in a waterlogged soil.

Spruce and fir trees growing on soils low in exchangeable Mg have exhibited reduced Mg in needle tissue, stunted growth, and needles that turn yellow, especially on the tips. Broadleaf trees severely deficient in Mg exhibit interveinal chlorosis on the older leaves, which in citrus trees sometimes coalesces into large, brilliant yellow-colored patches on either side of the midrib.

Forages with low contents of Mg compared to Ca and K can cause grazing animals to suffer from a sometimes-fatal Mg deficiency known as *grass tetany*. High levels of K can aggravate this problem by reducing Mg uptake.

Magnesium in Soil

Forms in Soil. The main source of plant-available Mg in most soils is the pool of exchangeable Mg on the clay–humus complex (Figure 9.3). As plants and leaching remove this Mg, the easily exchangeable pool is replenished by Mg weathered from minerals (such as dolomite, biotite, hornblende, and serpentine). In some soils, replenishment also takes place from a pool of slowly available Mg in the structure of certain 2:1 clays (see Section 8.3). Variable amounts of Mg are made available by the breakdown of plant residues and soil organic matter. In unpolluted forests, research suggests that atmospheric deposition, rather than rock weathering, may supply much of the magnesium used by trees. The inputs and outputs to the pools of plant-available calcium and magnesium in soils are summarized in Figure 15.5.

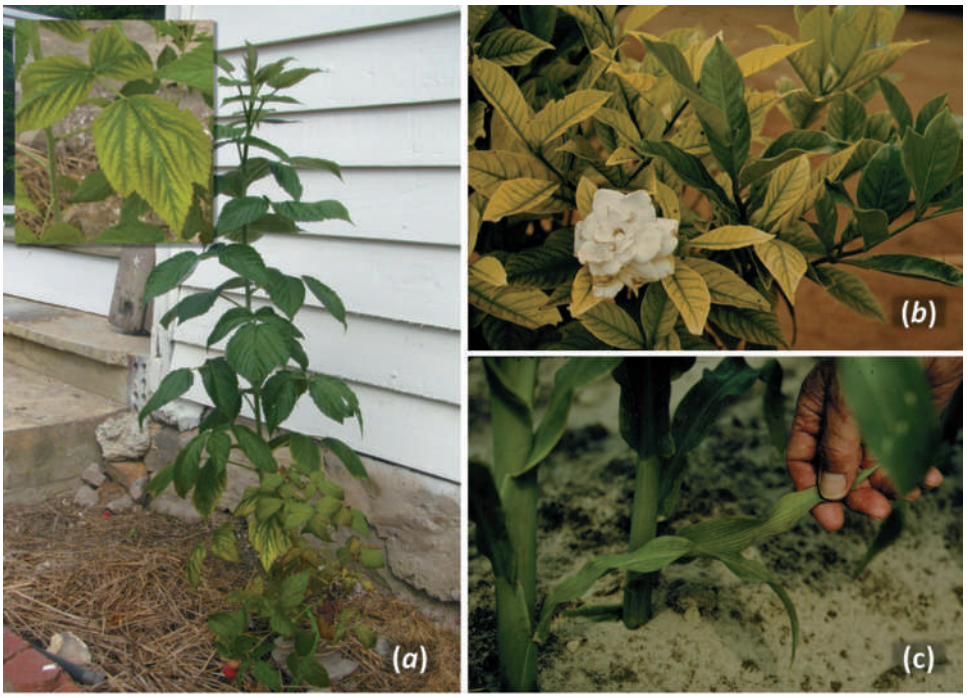

Figure 15.4 *Magnesium deficiency is most pronounced on the oldest leaves because Mg is easily re-mobilized to feed the newer leaves. Magnesium deficiency yellows the leaf tissue between the veins (a,b), which remain green (interveinal chlorosis). In monocots like corn which have parallel veins, the symptom appears as yellow and green stripes (c). Application of Mg fertilizer to a Mg-deficient plant will typically stimulate increased growth and eliminate the formation of new symptoms, but will not remove the chlorosis that formed on older leaves while the plant was deficient in Mg. The raspberry plant shown (a) was such a case.* (Photos courtesy of Ray R. Weil)

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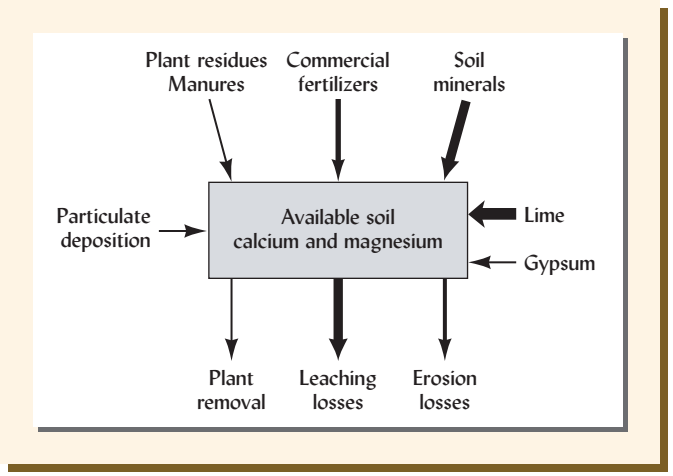

Figure 15.5 *The principal ways by which calcium and magnesium are supplied to and removed from the plant-available pool in soils. The relative thickness of the arrows indicate that major losses in humid region agricultural systems are usually through leaching and erosion and are usually replaced mainly by the addition of liming materials, with manures, mulches, and certain types of fertilizers providing secondary sources. In forest systems, losses by erosion and leaching are relatively small and may be equaled or exceeded by plant uptake and eventual loss in timber (especially whole tree) harvest. Calcium-rich particulate deposition (dust) provides inputs that are of considerable significance for many forest ecosystems.* (Diagram courtesy of Ray R. Weil)

Ratio of Calcium to Magnesium[2]

Being less tightly held (more easily leached) than Ca, exchangeable Mg commonly saturates only 5–20% of the effective CEC, as compared to the 60–90% typical for Ca in neutral to moderately acid soils (see Figure 9.5). Some agriculturists believe that optimum plant growth and soil tilth require a ratio of exchangeable Ca:Mg very near 6:1 (65% Ca and 10% Mg saturation of the CEC). This belief is based on a few out of date research studies from the mid-twentieth century and can lead to the wasteful use of soil amendments in an effort to achieve this so-called "ideal" Ca:Mg ratio (see Figure 16.49). Numerous research studies have shown that, in fact, plants grow very well and meet their Ca and Mg needs in soils with Ca:Mg ratios anywhere from 1:1 to 15:1. Well-documented research shows that soil aggregation and biological activity in most soils are also largely unaffected by a similarly wide range in this ratio. However, in soils with easily dispersed 2:1 clays, structural stability and flocculation can be adversely affected by high levels of exchangeable Mg (see Figure 8.11), though not nearly to the degree that monovalent K or Na cause such affects. Adding Ca to such soils in the form of gypsum or (if pH also needs to be raised) lime can improve infiltration and reduce erosion and leaching loss of nutrients (phosphorus especially) associated with dispersed clay. Also, even where plant and soil health are not likely to be affected by soil Ca: Mg ratios, the ratio of Ca to Mg content in plant tissue may be altered enough to influence the nutrition of grazing animals, and Ca or Mg mineral supplements may be needed in animal diets.

Soils formed from serpentine-rich rock, which is high in Mg but contains little Ca, offer an unusual but dramatic exception to the above statements. Exchangeable Mg in these soils is typically 3–9 times as plentiful as exchangeable Ca, giving a Ca:Mg ratio much smaller than 1.0. Serpentine-derived soils may, therefore, exhibit extreme imbalances between Ca and Mg, causing severe deficiency of Ca and toxicity of Mg for all but the few plant species that have evolved to grow in this unique soil environment. As a result, such serpentine-derived soils are characterized by natural vegetation that is sparse and stunted in comparison with that on nearby nonserpentine soils (Figure 15.6).

15.3 SILICON IN SOIL–PLANT ECOLOGY[3]

Scientists studying soil–plant ecology have long treated silicon (Si) as something of a neglected stepchild among the elements important to plants. As an example, in more than 100 years of publication of *The Nature and Properties of Soils* textbook, this is the first edition that devotes a section to silicon. Part of the reason for the neglect of silicon is the fact that this element has been proven to fit the definition of an essential nutrient (Section 1.2) for only one family

[2]For an objective review of how Ca/Mg ratios and cation balancing in general became widely, but wrongly, promoted for fertility management, see Kopittke and Menzies (2007).

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Figure 15.6 *Soils formed from serpentine rock provide an extreme case of imbalance between magnesium and calcium. (a) The Dubakella soil (clayey-skeletal, magnesic, mesic Mollic Haploxeralfs) in central California, USA, is an example of a soil formed from serpentine-rich ultrabasic rock. While the ratio of Ca/Mg in most soils is greater than 5.0, in this soil the ratio ranges from 0.5 in the A horizon to 0.1 in the Bt horizon. (b) The natural vegetation on the serpentinitic Dubakella soil appears sparse and stunted and consists of species (e.g., California scrub oak, manzanita, mountain brome grass, bottlebrush squirreltail, and needlegrass) uniquely adapted to the high magnesium, low Ca/Mg ratio soil environment. (c) Normal Ponderosa pine–blue oak forest vegetation grows on a nearby site with similar, but less serpentinitic, Secca soils (fine, mixed, superactive, mesic Mollic Haploxeralfs) in which the Ca/Mg ratio varies from 1.1 in the A horizon to 0.8 in the Bt horizon.* (Photos courtesy of Ray R. Weil)

of plants, and that family (Equisetaceae) mainly represents extinct species, save a single surviving genus, Equisetum (horsetails). Yet silicon is taken up in considerable amounts by all plants and has repeatedly been shown to enhance growth and function in a wide range of plant species. Therefore, silicon is sometimes referred to as a *beneficial element* for plants or a *quasi-essential nutrient*. For humans and other animals silicon *is* known to be an essential nutrient. However, too much Si intake along with limited water may cause kidney stones (siliceous renal calculi) in ruminant animals and humans. Silicon also plays many important, though often unrecognized, roles in soil processes, water quality, and in the biogeochemistry of such elements as carbon, calcium, and phosphorus.

Silicon in Soils

Silicon is the second most abundant element (after oxygen) in the Earth's crust as well as in most soils. Exceptions include some Histosols which contain mainly organic matter and some Oxisols from which weathering and leaching have removed most of the silicon.

Cycling of Silicon in Soils. As was discussed in Chapter 2, the silicate, quartz, is notoriously resistant to breakdown. However, most alumino-silicate minerals, including clay minerals and primary minerals such as Feldspars and Anorthite (shown in Eq. 15.1), undergo weathering reactions that release silicic acid to the soil solution:

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + \underset{\text{Carbon dioxide}}{2CO_2} + \underset{\text{Water}}{8H_2O} \rightarrow \underset{\text{Calcium}}{Ca^{2+}} + \underset{\text{Aluminum hydroxide}}{2Al(OH)_3} + \underset{\text{Silicic acid}}{2H_4SiO_4} + \underset{\text{Bicarbonate}}{2HCO^{-3}} \qquad (15.1)$$

In the pH range of most soils (pH 4–9), silicic acid is water soluble in the nondissociated form shown in Eq. (15.1). The silicic acid is subject to removal from the soil by both leaching and plant uptake. The weathering and removal of silicon is especially rapid in soils forming from ultrabasic rocks in the humid tropics. In humid regions, the leaching process typically

[3]For a review of the importance of silicon in plant ecology, see Cooke and Leishman (2011); for effects of silicon on crop plants, see Guntzer et al. (2012) and for roles of Si in pedology and biogeochemistry, see Sommer et al. (2006).

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sends some 5–50 kg Si ha^{-1} yr^{-1} toward the ocean. Once in the ocean, microscopic algae termed *diatoms* use much of the silicon to form their glasslike siliceous cell walls. In this manner the silicon weathered and leached from soils on land plays a major role in the global carbon cycle by controlling the deposition of carbon on the ocean floor in the form of dead diatoms.

Plants take up H_4SiO_4 in widely varying amounts (typically 25–500 kg Si ha^{-1} yr^{-1}). Plants transport the silicon into the stems and leaves where it is polymerized and deposited as biogenic (biologically formed) silica (SiO_2). This biogenic silica solidifies into the shape of the tissue cavities in which it is deposited, forming discrete, generally silt-sized particles termed **phytoliths** (literally *plant rocks*) (Figure 15.7). These characteristically shaped and long-lasting silica bodies are then deposited back to the soil with litter fall or the death of the plant. Biogenic silica from plants is also washed into the soil with throughfall. In the case of agricultural crops, the straw may contain a large proportion of the plant's phytoliths, so the return of these crop residues may be important in replenishing the soil's supply of biogenic silica. In the soil, some phytholiths slowly re-dissolve, providing an important source of relatively plant-available Si.

In other cases, phytoliths may remain nearly unchanged for thousands, even millions of years. The intricate shapes of such phytoliths found in today's soils may be used to identify the plant species that grew there in times long past. In some cases, organic carbon from the plant becomes occluded inside phytoliths, accounting for several percent of the mass. When these phytoliths are returned to the soil, they may provide significant amounts of long-lasting, protected soil carbon.

Phytoliths also contribute, along with other processes, to silicon accumulations during soil formation that result in a number of soil characteristics and even diagnostic horizons. Eluviation (downward movement) of silica bodies during wet seasons and their desiccation during dry season can result in the formation of hardened, silica-rich subsoil layers termed duripans. Silicon accumulations may also contribute to the formation of fragipans in humid regions (see Box 3.2) and hardsetting surface crusts in semiarid regions.

Silicon in Plants

Amounts and Forms Taken Up. The main form of silicon present in the soil solution is H_4SiO_4 (orthosilicic acid) and this is the form taken up by plants. Unlike most plant nutrient

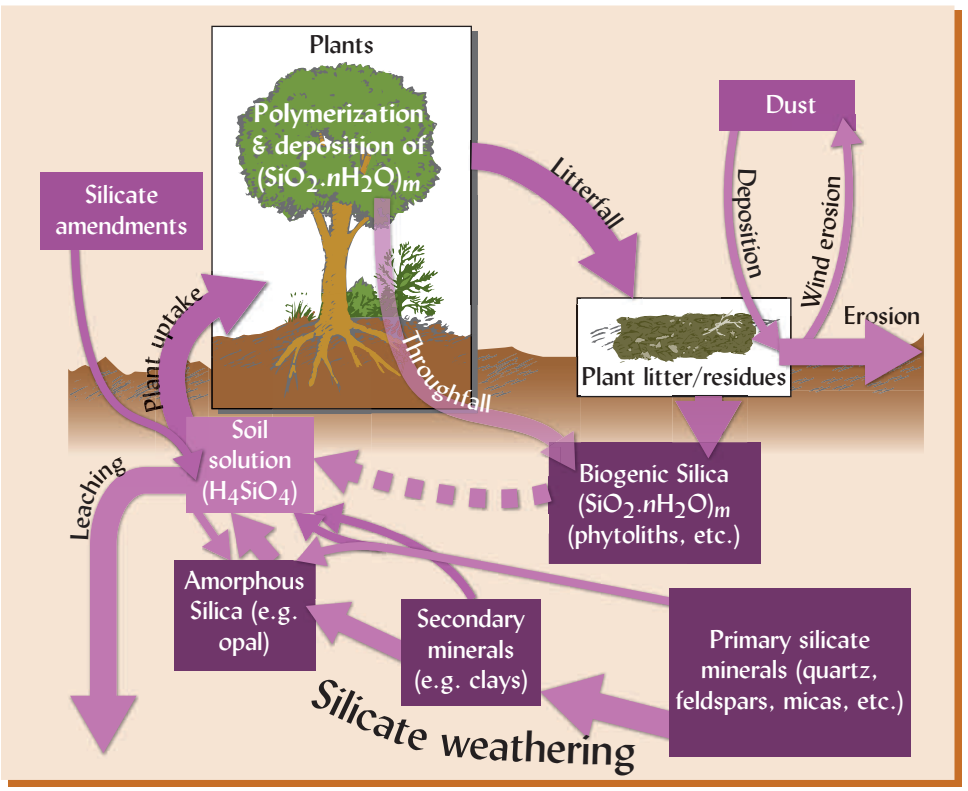

Figure 15.7 *The silicon cycle in soil-plant ecosystems. Silica is a major component of most soils and is found mainly in the primary rock-forming silicate minerals, as well as in the secondary silicate clay minerals. These minerals weather, with the aid of microbes and plant roots and release silicic acid (H_4SiO_4) to the soil solution. Plants take up H_4SiO_4 in widely varying amounts and transport it into the stems and leaves where it is polymerized and deposited as silica (SiO_2). This biogenic (biologically formed) silica solidifies into the shape of the tissue cavities in which is it deposited forming phytoliths. These characteristically shaped and long-lasting silica bodies are then deposited back to the soil with litter fall or washed into the soil with throughfall. There they may slowly re-dissolve or remain unchanged for thousands, even millions of years, the variable reactivity indicated by the broken arrow from this pool. Considerable silicon is leached out of the soil-plant system as silicic acid and ends up in the oceans.* (Diagram courtesy of Ray R. Weil)

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elements, silicon is not known to comprise part of any essential plant biomolecules. However, specific silicon transporter molecules have been identified in plants. These molecules bind reversibly with silicon to facilitate its movement from the soil solution across the cell membrane and into the root cortical cells, and from the root cortex into the xylem tissue—which acts as the plant's plumbing system to distribute the silicon throughout the shoot. Most of the H_4SiO_4 taken up is deposited as polymerized silica in phytoliths (see previous) (Figure 15.8).

The concentration of Si in plant dry matter is on par with the concentrations of such macronutrients as Ca, K, or Mg (Figure 15.9), though Si contents vary widely among different plant tissues and species. Three groups of plants are recognized based on their leaf tissue Si concentrations (% of dry matter) and on the mode of silicon uptake. Horsetails and wetland grasses (including rice) take up H_4SiO_4 through active transport mechanism such that the Si concentration is greater in the water entering the root than in the soil solution around the root. These Si accumulator plants typically contain Si to levels of 5–10% of their dry matter. Other grasses, including crops such as wheat, seem to take up H_4SiO_4 passively with water uptake such that the water entering the root cells contains about the same concentration of Si as the soil solution outside the roots. These plants generally contain 0.5–1.5% Si in their dry matter. Finally, most broadleaf (dicot) plants appear to restrict the passage of silicon into their roots and contain less than 0.25% Si in their dry matter.

Fertilization with Silicon. Because silicon is so abundant in most soils, it has commonly been assumed that plant growth and function must not be limited by insufficient amounts of this element. However, as was described for the nutrient element, potassium (Chapter 14), most of the silicon in soils is found as part of the structures of stable, rather insoluble minerals such that only a miniscule fraction of the total silicon present is in a form that plants can take up. Therefore, even in sandy soils made up largely of silicon (but in the inert form

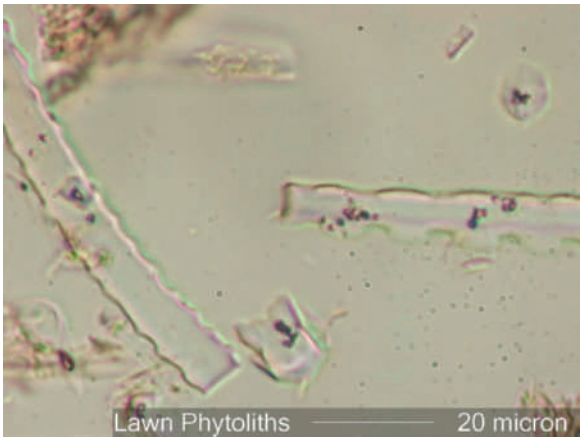

Figure 15.8 *Example of phytoliths (literally "plant rocks") made of silicon and also known as biogenic opal. These are seen under a light microscope and were obtained from grass leaves (lawn clippings).* (Image courtesy of E. Russell Crutcher, Microlabgallery.com, Redmond, WA)

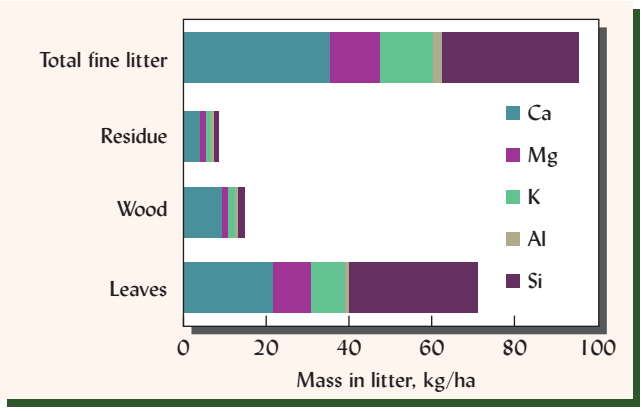

Figure 15.9 *Principal mineral elements recycled as litter fall in a tropical forest. Note that even in these highly weathered soils (Oxisols), the two elements present in largest quantity were Ca and Si. The fifth most abundant mineral element in the litter was Al, which was present in such small amounts as to be barely visible in the graph. The Si:Al ratio of the litter was about 10:1 while that of the soil beneath the litter was about 1:1 (the ratio in the dominant mineral, kaolinite). These data emphasize the importance of vegetation in cycling Si. In agro-ecosystems with cereals like wheat and rice the amount of silicon potentially returned to the soil in plant litter is even higher.* [Graphed from data in Lucas et al. (1993)]

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of quartz), plants may respond positively to the addition of relatively soluble sources of this element such as calcium silicates ($CaSiO_3$) from blast furnace slag (an industrial by-product from steel manufacture) or from the inosilicate mineral, Wollastonite ($Ca_3(Si_3O_9)$). The effectiveness of silicon "fertilizers" is dependent on the solubility of the silicon amendment and on soil properties such as clay mineralogy, soil pH, and inherent levels of soluble silica (Figure 15.10).

Roles of Silicon in Plants. Silicon strengthens and gives rigidity to plant cells, both as encapsulated phytoliths and as a component of the cell walls. The enhanced mechanical strength of plant cells benefits the plant in numerous ways. Increased Si helps crop plants like rice and sugarcane maintain a more erect leaf architecture that helps crowded agricultural plants capture more sunlight. The stronger silica-reinforced cells also resist physical damage, insect feeding, and may allow roots to better penetrate compacted soils. The latter effect of silicon has been documented in *Distichlis spicata*, a common grass in salt marshes.

Silicon and Plant Resistance to Stress. Many studies have shown that enhancing the supply of silicon can help alleviate many types of stress, both abiotic (e.g., stresses from salinity, drought, metal toxicity) and biotic (e.g., stresses from insects, fungal, and bacterial pathogens). The mechanisms by which Si protects plants from such stress are still the subject of active research (Table 15.3). Some of the protective effects appear to be related to the mechanical strengthening of cell walls by incorporation of large amounts of silicon either as phytoliths or in the cell wall component molecules making penetration by pests and pathogens more difficult. Other effects appear to be more physiological in nature, affecting plant metabolism and possibly hormone balance. Some evidence suggests that silicon enhances the plants' natural immune and defense systems, especially against foliar fungal diseases such as powdery mildew in plants of the cucumber family. Apparently added silicon can stimulate the plant's production of protective phenolic compounds.

In addition, some plant benefits are derived from reactions of soluble silicon in the soil without involving plant uptake (Table 15.3). Examples of this type of in-soil mechanism include: competition for sorption sites by which H_4SiO_4 can make $H_2PO_4^-$ more plant available and reactions with silicon that complex and detoxify such metal ions as Mn^{2+} and Al^{3+}. Soluble silicic acid in soils may also stimulate increased root exudation of antioxidants and phenolic compounds that protect plants from toxins. Finally, it should be noted that calcium silicates added to acid soils provide benefits as liming materials that raise soil pH (see Table 9.5 and Eq. 9.26).

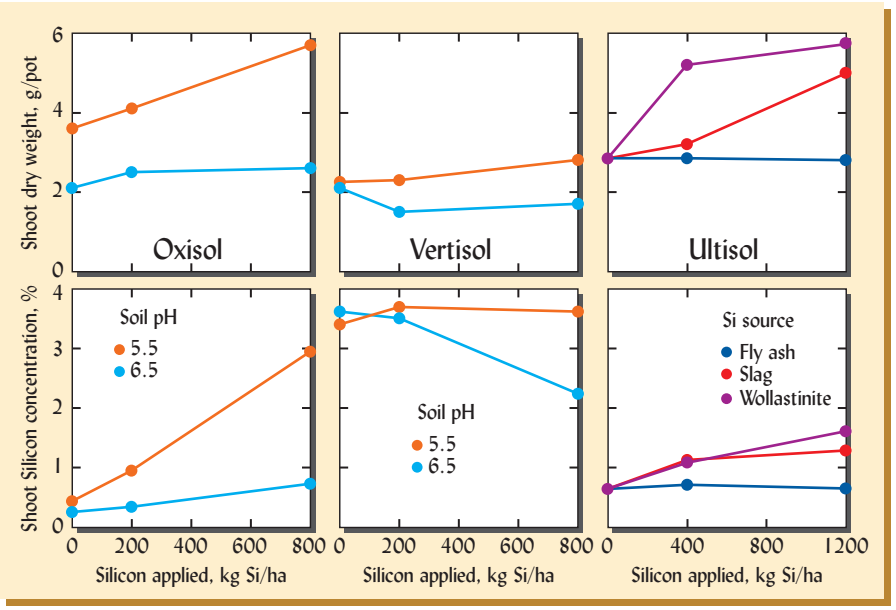

Figure 15.10 *Plant responses to added silicon are highly dependent on soil properties such as pH and clay mineralogy and on the solubility of the silicon amendment used. These studies used soils from Queensland, Australia and rice as the test plant. The upper panels show plant growth responses while the lower panels show changes in the Si concentration of the shoots. For the Oxisol and Vertisol, soil pH was adjusted to two levels and silicon was supplied as acidulated Wollastonite, an easily weathered calcium inosilicate mineral, $Ca_3(Si_3O_9)$. In the Oxisol which contained little or no silicate clay minerals, amending with Si and lowering the pH increased rice growth and Si uptake. In contrast, on the Vertisol dominated by 2:1 silicate clays, there was little effect of either practice. In a separate experiment using an Ultisol (Aquic Kandiustult), the initial soil pH was 5.6 and silicon was supplied either as Wollastinite, blast furnace slag or fly ash from coal combustion. The fly ash was completely ineffective as a source of Si for the plants.* [Graphed using data in Tavakkoli et al. (2011) and Haynes et al. (2013)]

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Table 15.3
THE NATURE OF SILICON EFFECTS ON PLANT GROWTH, FUNCTION, AND TOLERANCE OF ENVIRONMENTAL STRESSES

	Nature and location of the silicon mechanisms		
Specific silicon effect on plant growth	Chemical effects in the soil	Physiological effects in the plant	Mechanical[a] effects in the plant
Increased resistance to herbivory and diseases		X	X
Alleviation of P deficiency	X	X	
Alleviation of drought stress		X	X
Alleviation of Al and Zn toxicity	X	X	X
Alleviation of salt stress		X	
Reduction in lodging from strong wind and rain			X
Alleviation of Mn, Cd, and As toxicity	X	X	
Reduced absorption of nutrients (P, N) in excess		X	
Enhancement of K, P, Ca intake		X	
Alleviation of Fe toxicity	X		

[a]Related to the presence of silicon phytoliths and silicon reinforced cell walls.
Based largely on concepts in Guntzer et al. (2012).

Scientists still have much to learn about the roles and functions of silicon in plants and soils. There are still questions on how to best measure the plant availability of silicon in soils and in soil amendments, and on how to predict under what conditions one can expect Si applications to be effective. However, there can be little doubt that silicon plays important roles in soil–plant ecology and should be a consideration in soil fertility management.

15.4 DEFICIENCY VERSUS TOXICITY

At very low levels of a nutrient, reduced plant growth or function may occur because of a deficiency of the nutrient (*deficiency range*). As the level of nutrient is increased, plants respond by taking up more of the nutrient and increasing their growth. If a level of nutrient availability has been reached that is sufficient to meet the plants' needs (*sufficiency range*), raising the level further will have little effect on plant growth, although the concentration of the nutrient may continue to increase in the plant tissue. However, it is axiomatic that anything, including nutrients, can be toxic if taken in large enough amounts. At some level of availability, the plant will take up too much of the nutrient for its own good (*toxicity range*), causing adverse physiological reactions to take place. The relationship among deficient, sufficient, and toxic levels of nutrient availability is described in Figure 15.11.

For macronutrients, the sufficiency range is very broad and toxicity seldom occurs. However, for micronutrients the difference between deficient and toxic levels may be very narrow, making the possibility of toxicity quite real. For example, in the cases of boron and molybdenum, severe toxicity may result from applying as little as 3–4 kg/ha of available nutrient to a soil initially deficient in these elements. While the sufficiency range for other micronutrients is much wider and toxicities are not as likely from overfertilization, toxicities of copper, zinc, and nickel have been observed on soils contaminated by industrial sludges, manure from concentrated hog facilities, metal smelter wastes, and long-term application of copper fungicides. Toxicity of manganese is quite common in association with low soil pH and high soil content of Mn-containing minerals (see Sections 9.7 and 15.8). In certain forests it appears that the high ratios of manganese to magnesium or calcium are associated with the decline and death of sensitive tree species (Table 15.4). Iron is perhaps the most commonly deficient micronutrient

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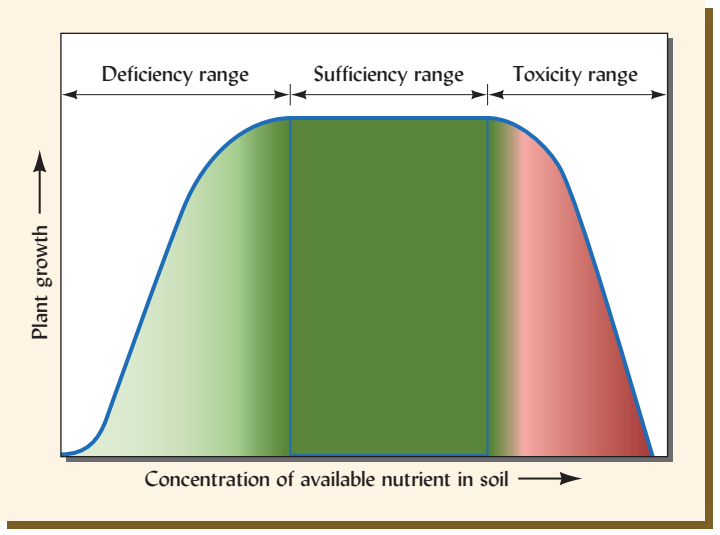

Figure 15.11 *The relationship between plant growth and the amount of a micronutrient available for plant uptake. Within the deficiency range, as nutrient availability increases, so does plant growth (and uptake, which is not shown here). Within the sufficiency range, plants can get all of the nutrient they need, and so their growth is little affected within this range. At higher levels of availability a threshold is crossed into the toxicity range, in which the amount of nutrient present is excessive and causes adverse physiological reactions that lead to reduced growth and even death of the plant.* (Diagram courtesy of Ray R. Weil).

Table 15.4
MAGNESIUM AND MANGANESE IN SOIL AND LEAVES IN RELATION TO DECLINING SUGAR MAPLES
Sugar maple death is related to nitrogen deposition caused soil acidification. Soil and foliage ratios of Mg/Mn indicated adverse conditions more consistently than did Ca/Al or Mg/Al.

			— Exchangeable ions in soil —				— Leaf content —		
Soil Great Group, parent material	Dead sugar maples, %	A horizon, pH_w	Ca	Mg	Mn	Mg/Mn	Mg	Mn	Mg/Mn
			— $cmol_c\ kg^{-1}$ —			ratio	— % —		ratio
Oxyaquic Glossudalfs, glacial till	3	5	4.4	0.627	0.033	19	0.172	0.048	9.2
Aquic Hapludults, shale and sandstone	64	4.08	0.66	0.123	0.121	1.0	0.082	0.254	0.7

Data for Northern Pennsylvania Forests selected from Kogelmann and Sharpe (2006).

for certain plants in neutral to alkaline soils, but it also can be toxic if it is applied or otherwise made available in too high concentrations (Figure 15.12f).

High levels of molybdenum may occur naturally in certain poorly drained alkaline soils. In some cases, enough of this element may be taken up by plants to cause toxicity, not only to susceptible species of plants but also to livestock grazing plants grown on these soils. Boron, too, may occur naturally in alkaline soils at levels high enough to cause plant toxicity. Because of the real potential for such plant toxicities, great care needs to be exercised in applying micronutrients, especially for maintaining balance among certain micronutrients.

In addition, irrigation water in dry regions may contain enough dissolved boron, molybdenum, or selenium to damage sensitive crops, even if the original levels of these trace elements in the soil were not very high. Therefore, it is prudent to monitor the content of these elements in water used for irrigation (see Section 10.8). Selenium does not appear essential for plants, but it is required by animals and can be toxic to both (see Section 15.10).

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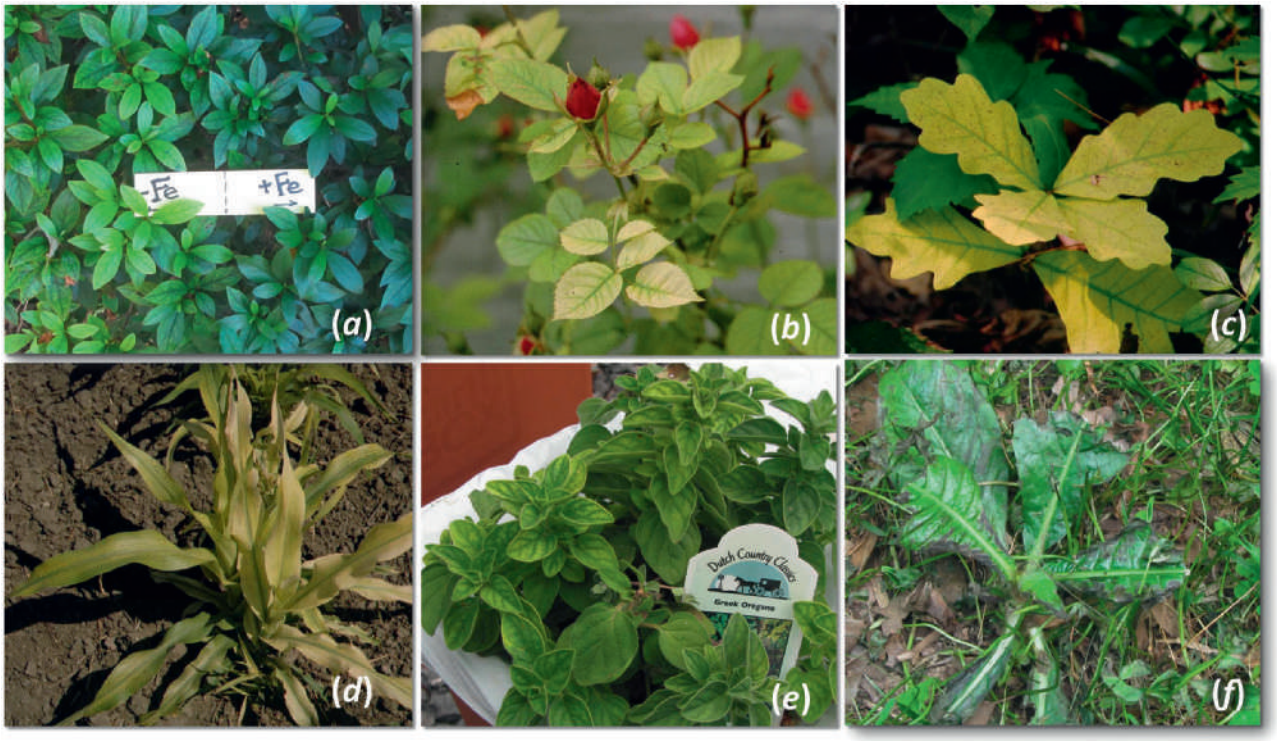

Figure 15.12 *Examples of deficiency (a–e) and toxicity (f) of the micronutrient iron. (a) Foliage of an iron-deficient azalea bush, with the right side having received a foliar application of an iron solution two days before the photo was taken. (b) This rose foliage exhibits the typical symptoms of iron deficiency, namely, interveinal chlorosis of the newest leaves. (c) The iron status of the oak seedling is severely deficient while that of the Virginia creeper growing in the same soil is normal, illustrating the influence of plant genetics on micronutrient availability. (d) A grain sorghum plant exhibits extreme iron deficiency due to the calcareous nature of the soil. (e) Iron-deficient basil growing in an artificial potting mix. (f) Here a concentrated iron solution has been used in an attempt to kill weedy broadleaf plants which are relatively sensitive to iron toxicity while leaving the less sensitive grasses unharmed.* (Photos courtesy Ray R. Weil)

15.5 MICRONUTRIENT ROLES IN PLANTS[4]

Micronutrients are required in very small quantities, their concentrations in plant tissue being one or more orders of magnitude lower than for the macronutrients (Figure 15.13). The ranges of plant tissue concentrations considered deficient, adequate, and toxic for several micronutrients are illustrated in Figure 15.14.

1. Intensive plant production practices have increased crop yields, resulting in greater removal of micronutrients from soils.
2. The trend toward more concentrated, high analysis fertilizers has reduced the use of impure salts and organic manures, which formerly supplied significant amounts of micronutrients.
3. Increased knowledge of plant nutrition and improved methods of analysis in the laboratory are helping in the diagnosis of micronutrient deficiencies that formerly might have gone unnoticed.
4. The importance of micronutrient deficiencies in human diets has become widely recognized. Evidence indicates that food grown on soils with low levels of trace elements may provide insufficient human dietary levels of certain elements, even though the crop plants themselves show no signs of deficiency.

[4]For overviews of micronutrients in global agriculture, see Alloway and Graham (2008) and Fageria (2009), the latter includes a complete chapter on each nutrient. For a detailed review of the micronutrients' physiological roles in plants, see Welch (1995).

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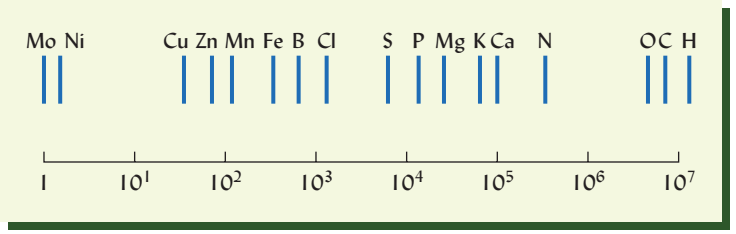

Figure 15.13 *Relative numbers of atoms of the essential elements in alfalfa at bloom stage, expressed logarithmically. Note that there are more than 10 million hydrogen atoms for each molybdenum atom. Even so, normal plant growth would not occur without molybdenum.* [Modified from Viets (1965)]

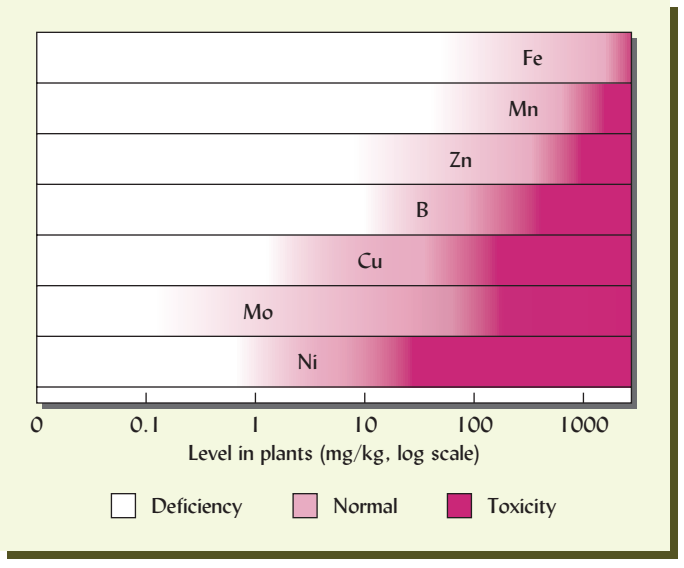

Figure 15.14 *Deficiency, normal, and toxicity levels in plants for seven micronutrients. Note that the range is shown on a logarithmic scale and that the upper limit for manganese is about 10,000 times the lower range for molybdenum and nickel. In using this figure, keep in mind the remarkable differences in the ability of different plant species and cultivars to accumulate and tolerate different levels of micronutrients.* (Diagram courtesy of Ray R. Weil, based on data from many sources)

Physiological Roles in Plants Micronutrients play many complex roles in plant nutrition. While most of the micronutrients participate in the functioning of a number of enzyme systems (Table 15.5), there is considerable variation in the specific functions of the various micronutrients in plant and microbial growth processes. For example, copper, iron, and molybdenum are capable of acting as electron carriers in the enzyme systems that bring about oxidation–reduction reactions in plants. Such reactions are essential steps in photosynthesis and many other metabolic processes. Zinc and manganese function in many plant enzyme systems as bridges to connect the enzyme with the substrate upon which it is meant to act. Micronutrients play important roles in plant defenses against pests and diseases. For example, through its catalysis of certain enzymes, manganese plays an important role in the mechanisms by which plants defend themselves from pathogen attack (Table 15.6).

Molybdenum and manganese are essential for certain nitrogen transformations in microorganisms as well as in plants. Molybdenum and iron are components of the enzyme *nitrogenase*, which is essential for the processes of symbiotic and nonsymbiotic nitrogen fixation (Figure 15.15). Molybdenum is also present in the enzyme *nitrate reductase*, which is responsible for the reduction of nitrates in soils and plants. Therefore, molybdenum is needed in larger quantities where nitrate is the main form of N available to plants.

Nickel, the element most recently shown to be essential to plants, is needed for the function of several important enzymes. *Urease*, the enzyme that breaks down urea into ammonia and carbon dioxide, requires Ni. Therefore, legumes deficient in nickel will accumulate toxic levels of urea in their leaves. In addition, seeds of cereal plants deficient in nickel are not viable and fail to germinate.

Zinc plays a role in protein synthesis, in the formation of some growth hormones, and in the reproductive process of certain plants. Copper is involved in both photosynthesis and respiration and in the use of iron. It also stimulates lignification of cell walls. The roles of boron have yet to be clearly defined, but this element appears to be involved with cell division, water

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Table 15.5
FUNCTIONS OF SEVERAL MICRONUTRIENTS IN HIGHER PLANTS

Micronutrient	Functions in higher plants
Zinc	Present in several dehydrogenase, proteinase, and peptidase enzymes; promotes growth hormones and starch formation; promotes seed maturation and production.
Iron	Present in several peroxidase, catalase, and cytochrome oxidase enzymes; found in ferredoxin, which participates in oxidation–reduction reactions (e.g., NO_3^- and SO_4^{2-} reduction and N fixation); important in chlorophyll formation.
Copper	Present in laccase and several other oxidase enzymes; important in photosynthesis, protein and carbohydrate metabolism, and probably nitrogen fixation.
Manganese	Activates decarboxylase, dehydrogenase, and oxidase enzymes; important in photosynthesis, nitrogen metabolism, and nitrogen assimilation.
Nickel	Essential for urease, hydrogenases, and methyl reductase; needed for grain filling, seed viability, iron absorption, and urea and ureide metabolism (to avoid toxic levels of these nitrogen-fixation products in legumes).
Boron	Activates certain dehydrogenase enzymes; facilitates sugar translocation and synthesis of nucleic acids and plant hormones; essential for cell division and development.
Molybdenum	Present in nitrogenase (nitrogen fixation) and nitrate reductase enzymes; essential for nitrogen fixation and nitrogen assimilation.
Cobalt	Essential for nitrogen fixation bacteria; found in vitamin B_{12}.
Chloride	Essential for photosynthesis and enzyme activation. Plays role in regulation of water uptake on salt-affected soils.

Table 15.6
EFFECT OF MANGANESE LEVELS ON THE INCIDENCE OF ROOT ROT AND ROOT PEROXIDASE ACTIVITY IN COWPEA[a]

Manganese catalyzes peroxidase, an exo-enzyme that aids the synthesis of both lignin and monophenols. The lignin acts as a mechanical and chemical barrier against fungal invasion, while monophenols are fungal toxins that may also act in defense of the plant. Mn fertilizer controlled root rot almost as well as the chemical fungicide Carbendazim.

	Cowpea tissue conc.			
Treatment	Mn, mg/kg	N, %	Disease incidence 10 days after sowing, %	Peroxidase activity index
Mn, 0 mg/kg soil	45	3.15	75	16
Mn, 5 mg/kg soil	78	2.54	47	24
Mn, 10 mg/kg soil	92	2.85	44	27
Carbendazim, 0.2% on seeds	45	3.43	31	31

[a]In low-fertility, pH 8.6 loamy sand inoculated with *Rhizoctonia bataticola*.
Data selected from Kalim et al. (2003).

uptake, and sugar translocation in plants. Iron is involved in chlorophyll formation and degradation and in the synthesis of proteins and nucleic acids. Manganese/seems to be essential for photosynthesis, respiration, and nitrogen metabolism.

The role of chlorine is still somewhat obscure; however, it is known to influence photosynthesis and root growth.

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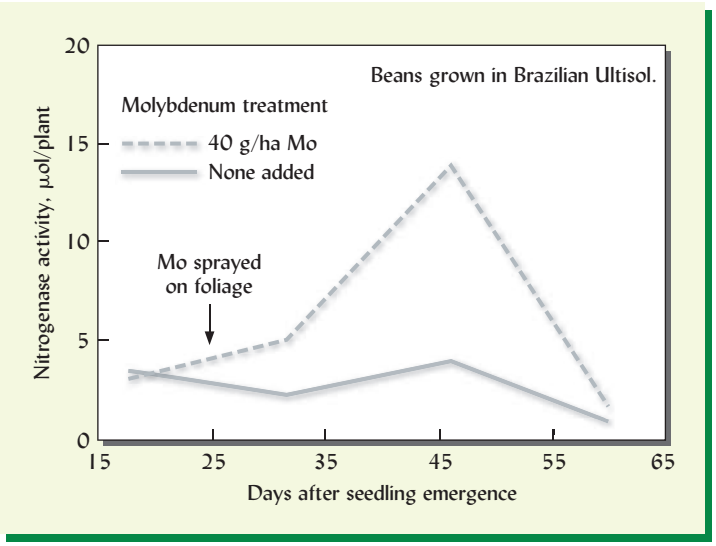

Figure 15.15 *Molybdenum deficiency in legumes inhibits N-fixation.* (Left) *An example of a major benefit coming from a very small application of a micronutrient, only 40 g/ha of molybdenum on bean leaves dramatically increased the plant level of the enzyme nitrogenase that is critical for the process of nitrogen fixation.* (Right) *Another legume crop, field peas, growing in a low-molybdenum Mollisol in Western USA exhibits symptoms similar to those of nitrogen deficiency.* [Graph based from data in Vieira et al. (1998); photo courtesy of Matt Hagny, Exapta Solutions, Salina Kansas]

Cobalt is essential for the symbiotic fixation of nitrogen. In addition, legumes and some other plants have a cobalt requirement independent of nitrogen fixation, although the amount required is small compared to that for the nitrogen-fixation process.

Deficiency Symptoms Visible plant symptoms are often helpful in diagnosing which micronutrient is deficient (see Table 15.7). The first thing to note is whether the symptoms are most pronounced on the youngest or oldest leaves on a plant. Most of the micronutrients are relatively immobile in the plant, that is, the plant cannot efficiently transfer the nutrient from older leaves to newer ones. Therefore, the concentration of the nutrient tends to be lowest, and the symptoms of deficiency most pronounced, in the younger leaves that develop after the supply of the nutrient has run low. In contrast the macronutrients (except Ca and S), are easily translocated in plants and so become deficient first in the *older* leaves. The pattern of most pronounced *micro*nutrient deficiency symptoms on the *younger* leaves is clearly illustrated for iron in Figure 15.12*b*,*e*, for manganese in Figure 15.16 and for zinc in Figure 15.17*a*.

In the case of zinc deficiency in corn (Figure 15.17*b*), broad white bands on both sides of the midrib are typical in young plants, but the symptoms may disappear as the soil warms up and the maturing plant's root system expands into a larger volume of soil. Mottled interveinal chlorosis (darker green area around the veins and light yellowish areas between the veins) on the younger leaves and the whorl of tiny leaves at the terminal end of the branch (a symptom known as *little leaf*) are characteristic of tree foliage suffering from too little zinc (Figure 15.17*a*).

Nickel deficiency has recently been found to be the cause of the "mouse ear" symptom of malformed, small-sized leaflets on pecan trees growing in sandy, low-nickel soils (Figure 15.18).

Boron deficiency generally affects plant growing points, such as buds, fruits, flowers, and root tips. Plants low in boron may produce deformed flowers (Figure 15.19*c*,*d*), aborted seeds, thickened, brittle, puckered leaves, or dead growing points. Young leaves may turn red on some plants (Figure 15.19*a*). In all of these cases, a small dose of boron applied at the correct time could make the difference between marketable or unmarketable plant products.

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Table 15.7
SYMPTOMS COMMONLY ASSOCIATED WITH MICRONUTRIENT DEFICIENCY OR TOXICITY ON PLANTS

Micronutrient	Symptoms of deficiency	Symptoms of toxicity
Fe	Young leaves show interveinal chlorosis, distinct green veins, entire leaf is white or yellow if severe. Roots grow profuse root hairs, bottle-brush effect.	Bronze or black discoloration of leaf margins, dark, slimy roots, mainly on submerged soils.
Mn	Young leaves, interveinal yellowing with greener veins, tissue near veins remains green, mottled appearance on dicots. Dead tissue in later stages. No lateral roots.	Dark green leaves with red flecks early, later bronze/yellow interveinal tissue. Patchy green colors. May induce Fe deficiency.
Zn	Young mature or old leaves depending on plant show yellowing, usually interveinal, rosetting, and dwarfing of leaves, broad white band on either side of corn leaf. Dark, shriveled leaves on turfgrass.	Pale leaves with necrotic interveinal lesions. Leaf tips water-soaked. Increased lateral roots, dense root system, barbed-wire pattern.
Cu	Young leaves yellow, rolled or dead leaf tips, stunted leaves and plants. Drooping leaves on trees.	Stunted plants, pale leaves—may induce Fe deficiency. Red coloration on leaf margins. Roots short with barbed-wire pattern.
Ni	Newest leaves chlorotic, small "mouse ear" leaves on pinnate-leafed trees, death of meristems.	Young leaflets distorted, white interveinal banding, dark green veins, irregular oblique streaking or white stripes brown patches. Brown, stunted roots.
Mo	May mimic N deficiency in legumes, mottled yellowing in young leaves, narrow, whip-like leaves in brassicas, whitish color, leaf tip death in grasses.	Reddish colors along leaf margins, normal-appearing roots.
B	Growing points of shoots and roots die. Reddish young leaves. Malformed buds, necrosis of internal tissues in fleshy stems, tubers, seeds. Stubby, bushy root system.	Interveinal chlorosis, marginal necrosis with distinct boundaries. Relative normal root appearance.
Cl	Yellowing and reduced leaf size. Later bronzing and necrosis. In cereals elongated necrotic patches.	Leaf tip and margin burn (necrosis), resembles K deficiency, but on younger leaves. Death of root tips.

Sources: Fageria et al. (2002); Baligar et al. (1998); Rashid and Ryan (2004); and others.

Figure 15.16 *Foliar symptoms of manganese deficiency are similar to those caused by insufficient iron. (a) Mn-deficient ornamental oak tree growing in a sandy Ultisol. (b) A soybean field on sandy Ultisols in Maryland, USA, exhibiting large areas with Mn deficiency. (c) Deficiency of Mn in soybeans, which like that of Fe, produces interveinal chlorosis on the newest leaves. Generally the veins remain darker green in the case of Fe deficiency.* (Photos courtesy of Ray R. Weil)

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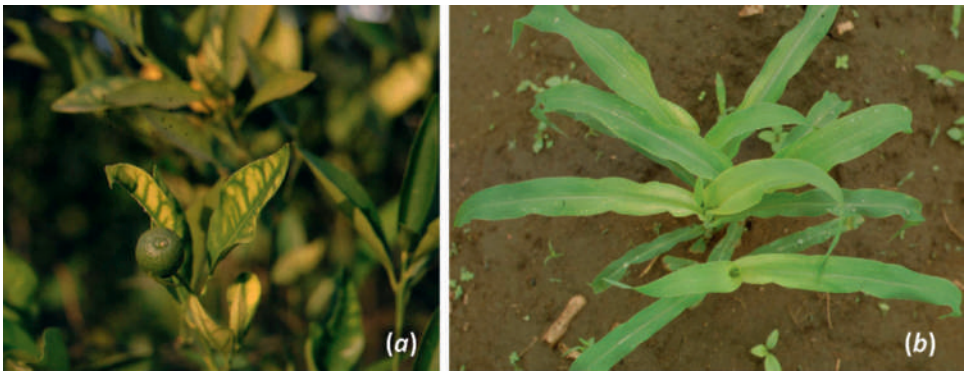

Figure 15.17 *Deficiencies of zinc produce unique foliar symptoms which vary with plant species. (a) A branch of a zinc-deficient citrus tree. Note the interveinal chlorosis with wide irregular green area along the veins and a shortened internode leading to a compact leaf whirl. Young corn plants (b) develop broad chlorotic bands (sometimes striped) on either side of the midrib.* (Photos courtesy of Ray R. Weil)

Figure 15.18 *Nickel deficiency on a pecan tree growing on sandy, low-nickel soil in Georgia, USA. Just before leaf formation in spring only the left side of the tree was sprayed with a $NiSO_4 \cdot 6H_2O$. The right side was not sprayed with Ni. A symptom characteristic of Ni deficiency on pecan trees is a malformation called "mouse-ear" (inset). In some older pecan orchards, accumulation of zinc in the soil from many years of applications to counter zinc deficiency seems to aggravate the nickel problem, possibly because Zn competes for the same uptake sites on the root membrane.* [Photos courtesy of Bruce W. Wood, USDA/ARS Southeastern Fruit and Nut Tree Research Lab. For details, see Wood et al. (2004)]

15.6 SOURCES OF MICRONUTRIENTS

Deficiencies and toxicities of micronutrients may be related to the total amounts of these elements in the soil. More often, however, these problems result from the chemical forms present in the soil and, particularly their solubility and availability to plants.

Inorganic Forms

Micronutrients sources vary markedly from soil to soil. Table 15.8 illustrates the wide variability in the content of these elements in soils and provides some typical values for micronutrient levels in soils and crop plants.

All of the micronutrients can be found to some extent in igneous rocks. Two of them—iron and manganese—occupy prominent structural positions in primary silicate minerals, such as biotite and hornblende. Others, such as cobalt and zinc, also may occupy structural positions as minor replacements for the major constituents of silicate minerals, including clays.

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Figure 15.19 *(a) A deficiency of boron caused the young leaves on this alfalfa plant to turn a reddish color. (b) More commonly, a lack of boron results in deformity or death of the plant growing points, as on the B starved bean plants in the right-hand pot whose terminal buds (arrow) have died and whose older leaves have thickened and crinkled in comparison to the B fertilized beans in the pot the left. (c) A misshapen rose, or* bullhead, *on a boron-deficient tea rose.*
(d) A well-formed bloom on the same plant after a solution containing boron was applied to the leaves and young buds.
(Photos courtesy of Ray R. Weil)

Table 15.8
MAJOR SOURCES OF PLANT MICRONUTRIENTS, RANGES AND REPRESENTATIVE CONTENTS OF THESE NUTRIENTS IN SOILS, ALONG WITH THEIR REPRESENTATIVE CONTENTS IN HARVESTED CROPS
The ratio of soil to crop contents emphasizes the primary need to increase the efficiency of plants in absorbing these nutrients from the soil.

			Representative contents of		
Element	Major sources	Range, kg/ha/15 cm	Soil, kg/ha/15 cm	Crop, kg/crop	Soil/crop ratio
Fe	Oxides, sulfides, silicates	20,000–220,000	56,000	2	28,000
Mn	Oxides, silicates, carbonates	45–9,000	2,200	0.5	4,400
Zn	Sulfides, carbonates, silicates	25–700	110	0.3	366
Cu	Sulfides, hydroxy carbonates, oxides	4–2,000	45	0.1	450
Ni	Silicates (e.g., serpentine), Fe, Ni, Si	10–2,200	45	0.02	2,250
B	Borosilicates, borates	8–200	22	0.2	110
Mo	Sulfides, oxides, molybdates	0.4–10	5	0.02	250
Cl	Chlorides	15–100	22	2.5	9

As mineral weathering and soil formation occur, oxides and, in some cases, sulfides of elements such as iron, manganese, and zinc are formed (see Table 15.8). Secondary silicates, including the clay minerals, may contain considerable quantities of iron and manganese and smaller quantities of zinc and cobalt. Ultramafic rocks, especially serpentinite, are high in nickel. In the same manner as calcium or aluminum ions, micronutrient cations released by

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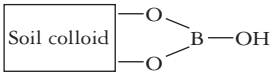
mineral weathering are subject to colloidal adsorption, (see Section 8.7). Minerals in soil particles eroded from distant sites and deposited as dust can add quantities of micronutrients that are significant in relation to the small amounts used by plants.

Micronutrient anions in soils, such as borate and molybdate, may undergo adsorption or reactions similar to those of described in Section 14.6 for phosphates. For boron, the adsorption may be represented as follows:



Chlorine, by far the most soluble of the group, is added to soils in considerable quantities each year through rainwater. Its incidental addition to soils in fertilizers and in other ways help make the deficiency of chlorine quite rare under field conditions. Chlorine is only very weakly adsorbed to soil colloids.

Organic Forms

Organic matter is an important secondary source of some of micronutrients and other trace elements. Several of these elements tend to be held as complex combinations by organic (humus) colloids. Copper is especially tightly held by organic matter—so much so that its availability can be very low in organic soils (Histosols). In uncultivated profiles, there is a somewhat greater concentration of micronutrients in the surface soil, much of it presumably in the organic fraction. Correlations between soil organic matter and contents of copper, molybdenum, and zinc have been noted. Although the elements thus held are not always readily available to plants, their release through decomposition is undoubtedly an important fertility factor. Animal manures are a good source of micronutrients, much of it present in organic forms.

Trace Elements Associated with Land-Applied Wastes Trace elements are common constituents of animal, industrial, and domestic wastes that are often applied to soils. Such waste materials are usually applied to soils for their organic matter and macronutrient (particularly nitrogen, phosphorus, and calcium) contents, but we must also recognize the significance of their trace element contents. Livestock manures are generally good sources of micronutrients, both in terms of quantities and plant availability. Small quantities of trace elements applied in these wastes can help alleviate nutrient deficiencies and prevent or even reverse soil micronutrient depletion in intensive agriculture. However, in some cases repeated applications of large quantities of wastes, especially sewage and industrial by-products, may cause some trace elements to accumulate to levels that are toxic not only to plants, but to the people and other animals that may consume the plants (see Chapter 18).

Forms in Soil Solution

The dominant forms of micronutrients that occur in the soil solution are listed in Table 15.9. The specific forms present are determined largely by the pH and by soil aeration (i.e., redox potential). Note that the cations are present in the form of either simple cations or hydroxy metal cations. The simple cations tend to be dominant under highly acid conditions. The more complex hydroxy metal cations become more prominent as the soil pH is increased.

Molybdenum is present mainly as MoO_4^{2-}, an anionic form that reacts with soil surfaces at low pH in ways similar to those of phosphorus (see Chapter 14). Although boron also may be present in anionic form at high pH levels, research suggests that undissociated boric acid (H_3BO_3) is generally dominant in the soil solution and is the form absorbed by plants.

The cycling of micronutrients through the soil–plant–animal system is illustrated in a generalized way by Figure 15.20. Although not every micronutrient will participate in every pathway shown in this figure, it can be seen that organic chelates, soil colloids, soil organic matter, and soil minerals all contribute micronutrients to the soil solution and, in turn, to growing plants. The primary sources of micronutrient elements are the original and secondary minerals, while the breakdown of organic matter releases ions to the soil solution. Removal of nutrients in crop or timber harvest reduces the soluble ion pool. If the rate of removal exceeds the rate of

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Table 15.9
FORMS OF MICRONUTRIENTS DOMINANT IN THE SOIL SOLUTION

Micronutrient	Dominant soil solution forms
Iron	Fe^{2+}, $Fe(OH)_2^+$, $Fe(OH)^{2+}$, Fe^{3+}
Manganese	Mn^{2+}
Zinc	Zn^{2+}, $Zn(OH)^+$
Copper	Cu^{2+}, $Cu(OH)^+$
Molybdenum	MoO_4^{2-}, $HMoO_4^-$
Boron	H_3BO_3
Cobalt	Co^{2+}
Chlorine	Cl^-
Nickel	Ni^{2+}, Ni^{3+}

From data in Lindsay (1972).

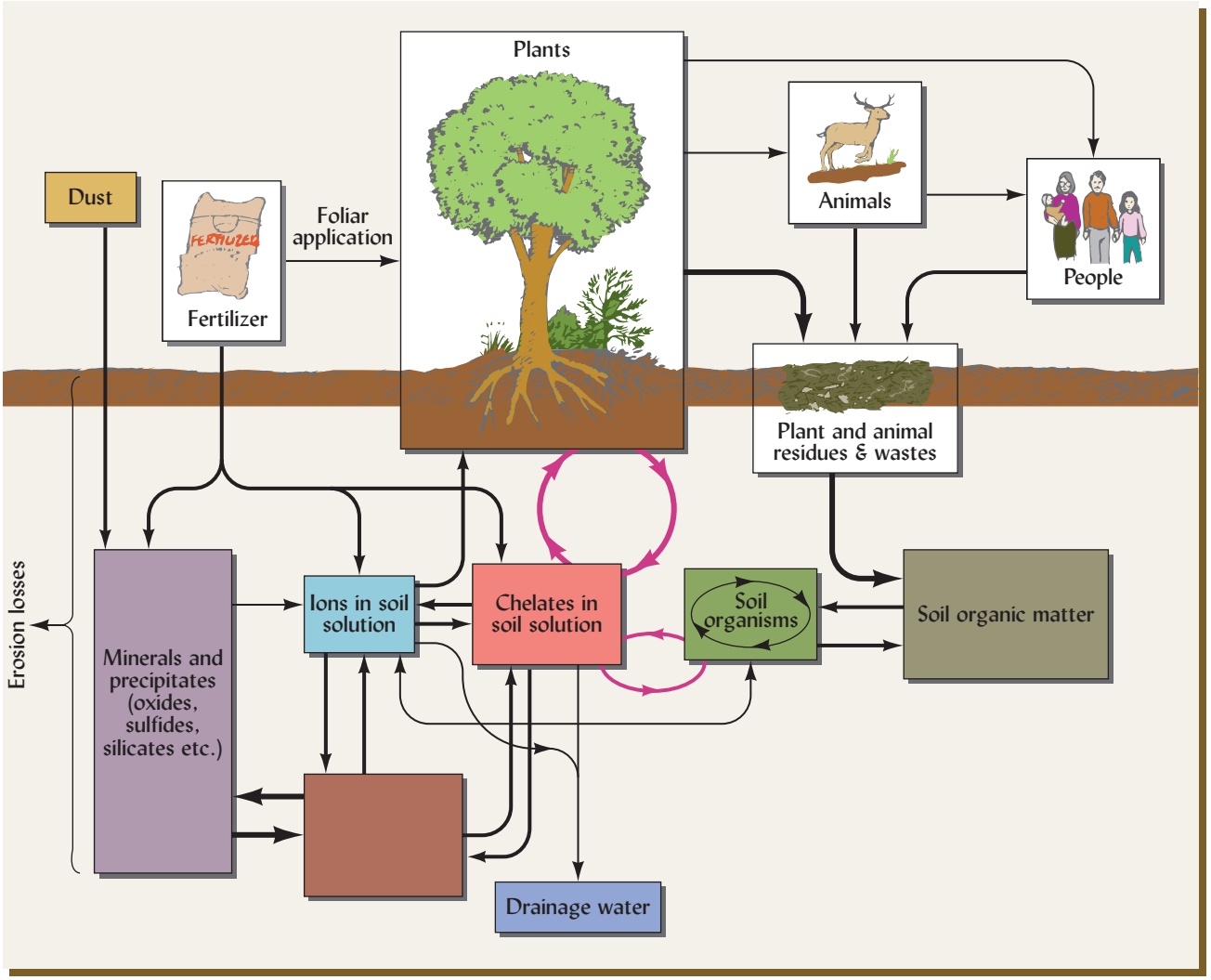

Figure 15.20 *Cycling and transformations of micronutrients in the soil–plant–animal system. Although all micronutrients may not follow each of the pathways shown, most are involved in the major components of the cycle. The formation of chelates, which keep most of these elements in soluble forms, is a unique feature of this cycle. Also, for micronutrients, dust and other forms of atmospheric deposition can be significant additions.* (Diagram courtesy of Ray R. Weil)

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replenishment by mineral weathering and atmospheric deposition, the soil supply may need to be replenished with manures or chemical fertilizers to avoid nutrient deficiencies. As we turn our attention to micronutrient availability, it will be helpful to refer back to Figure 15.20 to see the relationships among the processes involved.

15.7 FACTORS INFLUENCING THE AVAILABILITY OF THE TRACE ELEMENT CATIONS

Trace element cations including iron, manganese, zinc, copper, and nickel are each influenced in a characteristic way by the soil environment. However, certain soil factors have the same general effects on the availability of all of them.

Soil pH

The micronutrient cations are most soluble and available under acid conditions (Figure 15.21). In fact, under these conditions, the soil solution concentrations or activities of one or more of these elements (most commonly manganese) may become sufficiently high as to be toxic to many plants. As indicated in Chapter 9, one of the primary reasons for liming acid soils is to reduce the solubility of manganese and aluminum.

If the pH increases, the ionic forms of the micronutrient cations change first to the hydroxy ions and, finally, to the insoluble hydroxides or oxides of the elements. The following example uses the ferric ion as typical of the group:

$$\underset{\text{Simple cation (soluble)}}{Fe^{3+}} \xrightarrow{OH^-} \underset{\text{Hydroxy metal cations (soluble)}}{Fe(OH)^{2+}} \xrightarrow{OH^-} Fe(OH)_2^{+} \xrightarrow{OH^-} \underset{\text{Hydroxide (insoluble)}}{Fe(OH)_3} \qquad (15.2)$$

All of the hydroxides of the micronutrient cations are relatively insoluble—some more so than others. The exact pH at which precipitation occurs varies from element to element and between oxidation states of a given element. For example, the higher valence states of iron and manganese form hydroxides that are much more insoluble than their lower-valence counterparts. In any case, the principle is the same—at low pH values, the solubility of micronutrient cations is high, and as the pH is raised, their solubility and availability to plants decrease. Overliming an acid soil often leads to deficiencies of iron, manganese, zinc, copper, and sometimes boron. Such deficiencies associated with high pH occur naturally in many of the calcareous soils of arid regions.

The general desirability of a slightly acid soil (with a pH between 6 and 7) largely stems from the fact that for most plants, this pH condition allows micronutrient cations to be

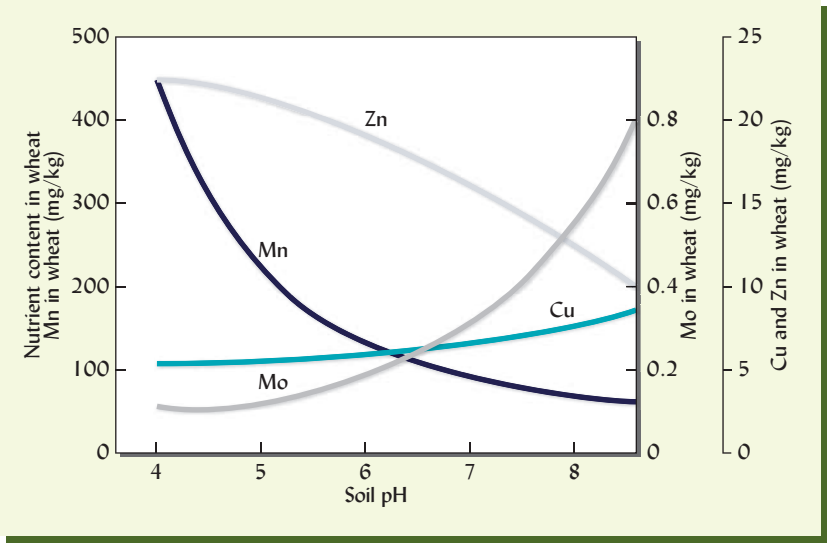

Figure 15.21 *Effect of soil pH on the concentrations of manganese, zinc, copper, and molybdenum in wheat plants. The plants were grown in soils from different countries around the world. The molybdenum levels are extremely low, but increase with increasing pH. Manganese and zinc levels decrease as the pH rises, while copper is little affected.* [Drawn from data in Sillanpaa (1982)]

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soluble enough to satisfy plant needs without becoming so soluble as to be toxic (see Figure 9.22). Certain plants, especially those that are native to very acid soils, have difficulty taking up iron and other micronutrients unless the soil is quite acid (pH about 5). Such acid-loving plants therefore become deficient in these elements when the soil pH is high enough to reduce iron solubility (usually above pH 5.5; see Figure 15.22, *left*). Section 9.7 gives more specific information on the pH preferences of various plants.

Zinc availability, like that of iron, is reduced when soil pH is raised by liming. However, in addition to the pH effects, the addition of high-magnesium liming materials (e.g., dolomitic limestone) further decreases zinc availability, because zinc is tightly adsorbed to dolomite and magnesium carbonate crystal surfaces. Zinc deficiency may also be aggravated by interaction between zinc and magnesium in the plant.

Oxidation State

The trace element cations iron, manganese, nickel, and copper occur in soils in more than one valence state. The lower valence states indicate that the atoms have gained electrons and the elements are considered *reduced*; in the higher valence state they have lost electrons and are *oxidized.* Metallic cations generally become reduced when the oxygen supply is low, as occurs in wet soils containing decomposable organic matter. Reduction can also be brought about by organic metabolic reducing agents, such as NADPH or caffeic acid, produced by plants and microorganisms in the soil. Oxidation and reduction reactions in relation to soil aeration and drainage are discussed in Sections 7.4 and 7.5.

The changes from one valence state to another are, in most cases, brought about by microorganisms and organic matter.[5] In some cases, the organisms may obtain their energy directly from the inorganic reaction. For example, the oxidation of manganese from Mn(II) in manganous oxides (MnO) to Mn(IV) in manganic oxides (MnO_2) can be carried out by certain bacteria and fungi. In other cases, organic compounds formed by microbes or plant roots may be responsible for the oxidation or reduction.

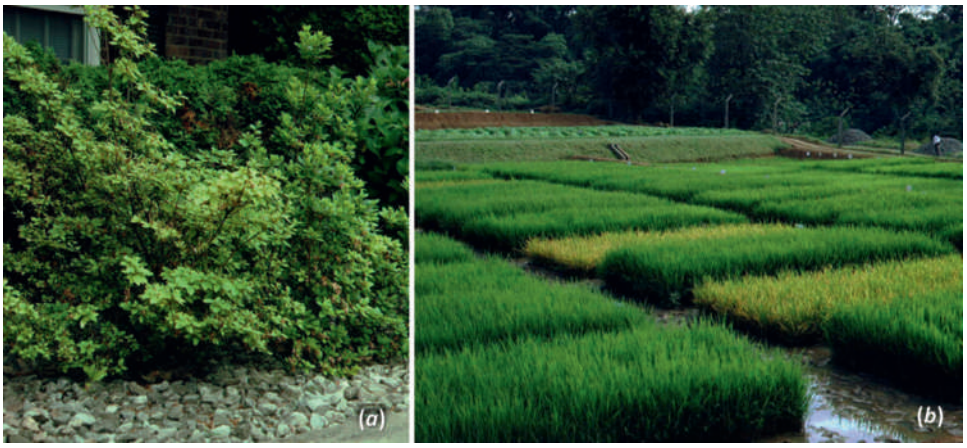

Figure 15.22 *How soil pH and redox potential can influence iron availability.* (Left) *The chlorotic foliage of these azaleas is a sign of iron deficiency inadvertently induced by a too-high soil pH. In this case, the iron deficiency was caused by the use of decorative white gravel made of marble. Marble consists mostly of calcium carbonate. Rainwater percolating through the gravel dissolved enough of this material to raise the pH gradually from 5.2 to 6.0. At pH 6.0 the solubility of iron is too low for the acid-loving azaleas to obtain what they need. Calcium leaching from concrete walkways can have a similar effect on acid-loving vegetation growing in adjacent soil.* (Right) *Plots of chlorotic (yellowish) plants indicate iron toxicity in certain strains of rice in a breeding nursery. The rice is growing on a flooded terrace build in iron-rich tropical Ultisols. The anaerobic conditions under the flood water stimulated the reduction of insoluble Fe^{3+} compounds to the much more soluble Fe^{2+} form. The dissolved Fe^{2+} then moved downhill with the water from terrace to terrace, accumulating in the foreground.* (Photos courtesy of Ray R. Weil)

[5]For a review of microbial reduction of certain trace elements, see Lovley (1996).

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Interaction of Soil Reaction and Aeration. At pH levels common in soils, the oxidized states of iron, manganese, and copper are generally much less soluble than are the reduced states. The hydroxides (or hydrous oxides) of these high-valent forms precipitate even at low pH values and are extremely insoluble. For example, the hydroxide of trivalent ferric iron precipitates at pH values of 3.0–4.0, whereas ferrous hydroxide does not precipitate until a pH of 6.0 or higher is reached.

The interaction of soil acidity and aeration in determining micronutrient availability is of great practical importance. Iron, manganese, and copper are generally more available under conditions of restricted drainage or in flooded soils (Figure 15.23). Very acid soils that are poorly drained may supply toxic quantities of iron and manganese. For example, manganese toxicity has been reported to occur when certain high-manganese acid soils are thoroughly wetted during irrigation. Andisols (volcanic soils) with high-organic-matter melanic epipedons are known to cause manganese toxicity problems when they are wet by heavy rains. Rice paddies established on red iron-rich upland soils after terracing and flooding provide an example of how dramatically reduction reactions can increase in the solubility of iron—and therefore its mobility and possible availability and even toxicity to plants (Figure 15.22, *right*). Iron toxicity is much less apt to occur under well-drained conditions, unless soil pH is very low. The influence of aeration can be quite complex in the case of zinc (Box 15.1).

Well-oxidized calcareous soils combine high soil pH levels with good aeration. These characteristics commonly cause plant deficiencies of available iron, zinc, or manganese even though adequate total quantities of these trace elements are present in the soil. Hydroxides of the high-valence forms of these elements are too insoluble to supply the ions needed for plant growth. In contrast, at high soil pH values, molybdenum availability may be excessively high. **Molybdenosis** is a potentially fatal disorder caused by excessive molybdenum in the diet of livestock grazing plants grown on certain very high pH soils.

Plant Genetic Differences. There are marked differences among plant species and strains with regard to their ability to obtain micronutrients from low-solubility sources in soils. One example is seen in the sensitivity of different plant varieties to iron deficiency in soils with high pH. Certain plants can apparently solubilize iron in the immediate vicinity around their roots. Iron-efficient varieties respond to iron stress by acidifying the immediate vicinity of the roots and by excreting compounds capable of donating electrons to reduce Fe(III) to the much more soluble Fe(II) form, with a resultant increase in its availability (Figure 15.25). It appears that most of the iron-reducing activity is concentrated in the root hairs of actively growing young roots (Figure 15.26).

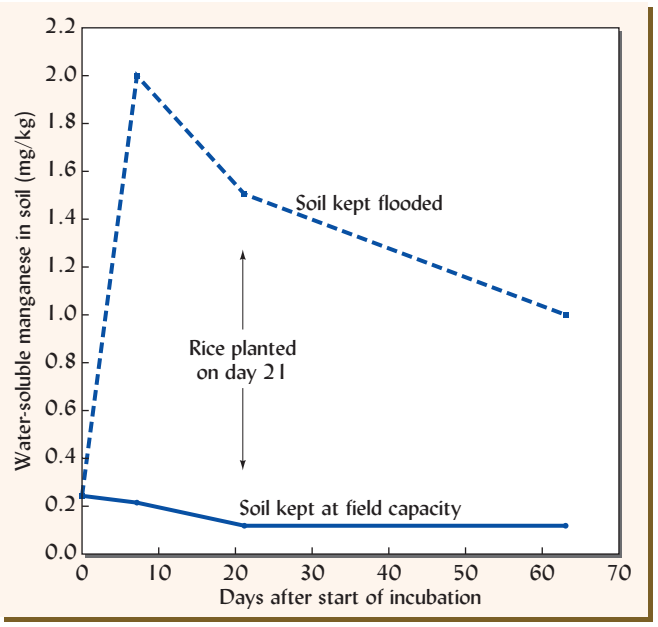

Figure 15.23 *Effect of flooding on the amount of water-soluble manganese in soils. The data are the averages for 13 unamended Ultisol horizons with initial pH values ranging from 3.9 to 7.1.* [Data from Weil and Holah (1989)]

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BOX 15.1

COMPLEX SOIL CHANGES YIELD ZINC-DEFICIENT RICE

China's rice farmers, who are adapting new systems of growing rice in upland aerated conditions instead of traditional flooded rice paddies, have run into some unforeseen micronutrient problems. Although they saw no Zn deficiency in the traditional flooded rice, they are finding their rice to be Zn deficient on the same soils once they switch to the drained, aerated system. Many soils used for flooded rice cultivation in northern China have very low levels of available zinc to begin with, less than 1.0 mg Zn/kg soil extractable by the chelating agent DTPA. (Chelating agents are often used in testing soils for micronutrient availability, as they somewhat mimic the action of the plant root, as explained in Section 15.8.)

The low Zn availability in these soils is related to the high pH, high carbonate levels, and low redox potential of the flooded soils. Yet, these soils were able to make available just enough Zn to avoid deficiencies in rice grown under flooded conditions. However, when the soils are drained for the aerated rice production system, at least five changes occur. Of these, two processes are likely to increase the availability of zinc and three are likely to decrease it:

Soil changes likely to increase zinc availability:

- Iron in the soils is oxidized, causing acidification that should increase Zn solubility.
- Decomposition of soil organic matter is accelerated, releasing the Zn previously adsorbed.

Soil changes likely to decrease zinc availability:

- The oxidized iron soon precipitates as $Fe[OH]_3$, which can strongly adsorb Zn from solution, decreasing its availability.
- Aeration stimulates nitrification, causing plants to take up more NO_3^- and less NH_4^+, in turn causing less rhizosphere acidification (see Section 9.1) and lower Zn solubility.
- The drained soil contains less water-filled pore space, thus providing few pathways through which Zn can move by diffusion and mass flow toward the roots.

With so many processes working in opposite directions, the net effect on Zn bioavailability is difficult to predict on theoretical grounds, but experiments with five strains (genotypes) of rice showed that Zn is consistently less available under the aerated conditions (Figure 15.24). For some rice genotypes, reduction in Zn availability keeps their uptake below the level considered sufficient for good growth. Fortunately, several other rice genotypes are able to obtain enough Zn for their needs, even under the aerated system. Soil scientists, in collaboration with plant breeders, are attempting to sort things out to allow China's rice farmers to take advantage of the new, more productive aerated system without being held back by a micronutrient deficiency.

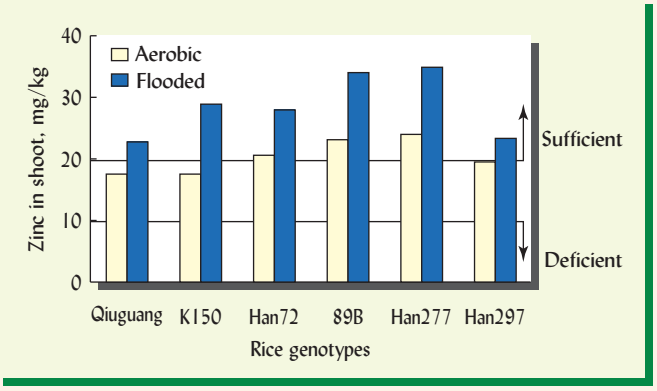

Figure 15.24 *Zinc concentration at tillering stage in rice plants under aerated and flooded production systems without Zn application.* [From Gao et al. (2006)]

Other Inorganic Reactions

Micronutrient cations interact with silicate clays in two ways. First, they may be involved in cation exchange reactions much like those of calcium or aluminum. Second, they may be tightly bound or fixed to certain silicate clays, especially the 2:1 type. Zinc, manganese, and iron ions sometimes occur in the crystal structure of these clays. Depending on conditions, they may be released from the clays or fixed by them in a manner similar to that by which potassium is fixed (see Section 14.13). The fixation may cause serious deficiency in the case of zinc, because this element is present in soil in such small quantities (see Table 15.8).

The application of large quantities of phosphate fertilizers can adversely affect the uptake of both iron and zinc. This interference with micronutrient uptake is one more reason (in addition to those given in Chapter 14) that phosphate fertilizers should be used in only quantities required for good plant growth.

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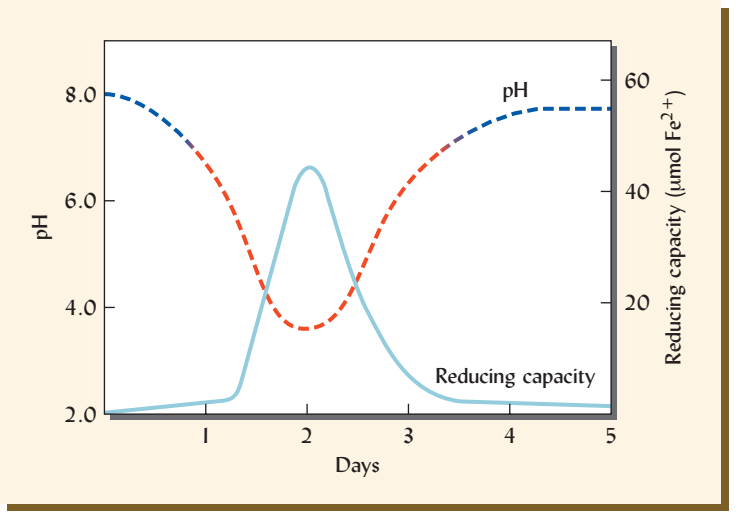

Figure 15.25 *Typical pattern of changes in rhizosphere chemistry brought about by root exudation in response to iron deficiency. When the plant becomes iron-stressed, plant roots exude organic acids that lower the pH over a period a few days. Simultaneously, the roots also exude agents that increase the capacity to reduce iron from Fe^{3+} to Fe^{2+} in the immediate vicinity of the roots. Iron is therefore solubilized and taken up by the plant, the stress is alleviated, and pH and reducing conditions return to normal. The roots of some plants also exhibit a daily pattern of exuding siderophores, producing these iron-binding compounds during the day but not at night when iron is not needed for photosynthesis.* (Diagram courtesy of Ray R. Weil)

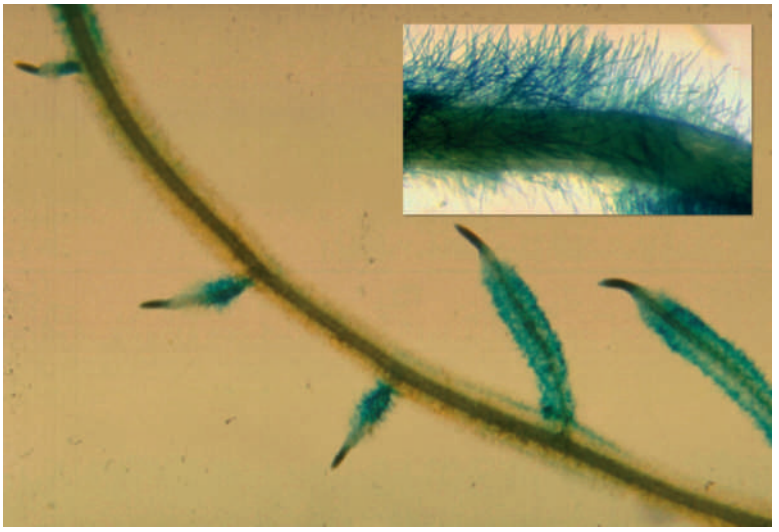

Figure 15.26 *Reduction of iron by tomato roots is made visible by staining live roots with a chemical that turns dark blue when the iron in the stain is reduced to the Fe(II) form. Reduction occurred only in the mature part of young branch rootlets. In the white zone just behind the root tip, young cells had not yet developed the reducing mechanisms. The close-up (inset) shows that the reduction reaction occurs only in the root hairs. The main part of the root remains undarkened.* (Photos courtesy of Paul Bell, University of Maryland and Rufus Cheney, U.S. Dept. of Agriculture, Agricultural Research Service)

Lime-Induced Chlorosis

Iron deficiency in fruit trees and many other plants is encouraged by the presence of the bicarbonate ion. Irrigation waters containing bicarbonate increase the level of this ion in some soils. In other soils, especially poorly buffered sandy soils, the problem stems from application of more lime than is needed to reach the proper pH. The chlorosis results from iron deficiency in soils with high pH because the bicarbonate ion interferes with iron metabolism, and iron solubility in the soil is greatly reduced because of the too high pH. These conditions also pertain to certain calcareous soils of dry regions (see Section 10.1 and Figure 10.10).

Organic Matter

Organic matter, organic residues, and manure applications affect the immediate and potential availability of micronutrient cations. Certain water-soluble organic compounds form organometallic complexes that enhance micronutrient availability—and these are considered in Section 15.8. Other organic compounds react with micronutrient cations to form water-insoluble complexes that protect the nutrients from interactions with mineral particles that can bind them in even more insoluble forms. Some organometallic complexes provide slowly available nutrients as they undergo microbial breakdown. Figure 15.27 illustrates the large role that sorption on soil organic matter (and iron oxides) plays in the solubility of Cu and the much smaller role of organic matter with regard to Zn.

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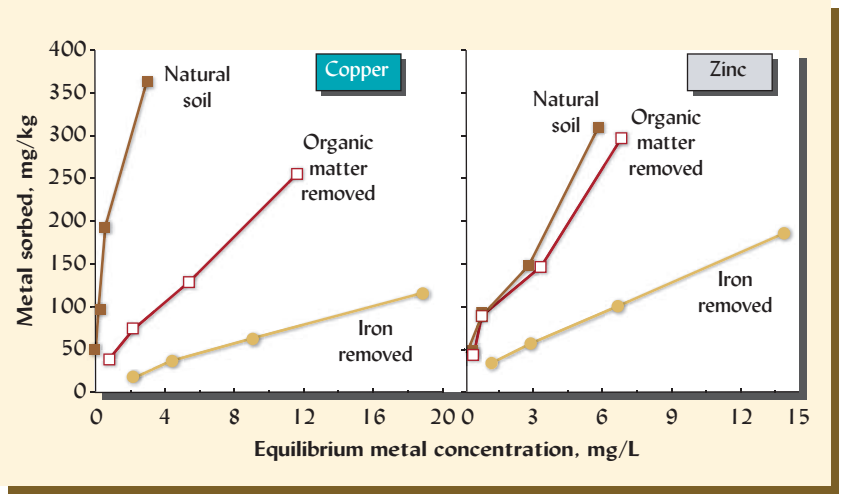

Figure 15.27 *Sorption of Cu and Zn in a tropical Alfisol as affected by removal of the organic and iron components of the soil. Removal of organic matter greatly reduced the sorption of Cu but had little effect on Zn. The subsequent removal of "free" iron from soil particle surfaces reduced the sorption of both metals. The metal binding sites on both the iron coatings and the organic matter were more selective for Cu than for Zn. The data illustrate that reactions with organic matter and amorphous iron are the major controls on Cu sorption, whereas Zn is held mainly by the iron and probably by cation exchange reactions.* [Graphed from data in Agbenin and Olojo (2004)]

Deficiencies of copper and, to a lesser extent, manganese are often found on poorly drained soils high in organic matter (e.g., Histosols and other wetland soils). Zinc is also retained by organic matter, but deficiencies stemming from this retention are not common.

Microbial decomposition of organic matter in plant residues and animal manures can result in the release of micronutrients by the same mechanisms that stimulate the release of macronutrient ions. As is the case for macronutrients such as nitrogen, however, temporary deficiencies of the trace elements may occur due to microbial immobilization (see Section 12.3) when high-carbon content organic residues are added.

Micronutrient-rich organic products can be used as a nutrient source on soils deficient in available trace elements. For example, composts of iron-enriched organic materials, such as forest by-products, animal manures, and plant residues, have been found to be effective on iron-deficient soils.

Role of Mycorrhizae

The roots of most plants interact symbiotically with certain fungi to form mycorrhizae (fungus roots), which are far more efficient than normal plant roots in several respects. The nature of the mycorrhizal symbiosis and its importance in phosphorus nutrition were described in Sections 11.9 and 14.3, but it is worth mentioning here that mycorrhizae can also increase plant uptake of micronutrients (Table 11.6). Crop rotations and other practices that encourage a diversity of mycorrhizal fungi may thereby improve micronutrient nutrition utilization (Figure 15.28).

Surprisingly, mycorrhizae also appear to protect plants from excessive uptake of micronutrients and other trace elements where these elements are present in potentially toxic concentrations. Seedlings of such trees as birch, pine, and spruce are able to grow well on sites contaminated with high levels of zinc, copper, nickel, and aluminum only if their roots are sheathed by ectomycorrhizae. The mycorrhizae apparently help exclude these metallic cations from the root stele and prevent long-distance transport of metal cations within the plant.

15.8 ORGANIC COMPOUNDS AS CHELATES

The cationic micronutrients react with certain organic molecules to form organometallic complexes called **chelates**. If these complexes are soluble, they increase the availability of the micronutrient and protect it from precipitation reactions. Conversely, formation of an insoluble complex will decrease the availability of the micronutrient.

Organic Chelating Agents

A chelate (from the Greek *chele*, claw) is an organic compound in which two or more atoms are capable of bonding to the same metal atom, thus forming a ring. These organic molecules may

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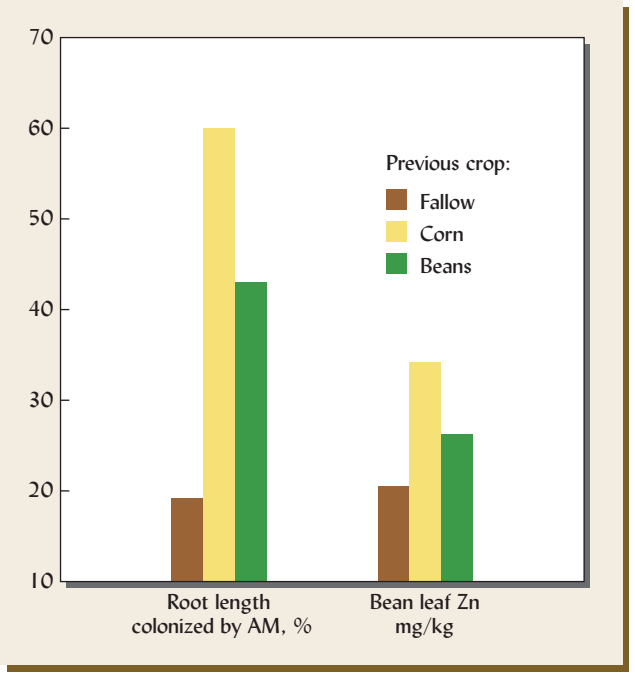

Figure 15.28 *Effect of crop rotation on uptake of zinc and formation of mycorrhizae by beans. The bean crop, grown with furrow irrigation on an Aridisol (Calcid) in Idaho, USA, was preceded by either a corn crop, a bean crop, or a year of bare fallow. The corn-followed-by-bean rotation favored both arbuscular mycorrhizae (AM) formation and zinc uptake by the second-year bean crop. The fallow period deprived the AM fungi of the host plants they need to survive (see Section 11.9).* [Graphed from data from Hamilton et al. (1993)]

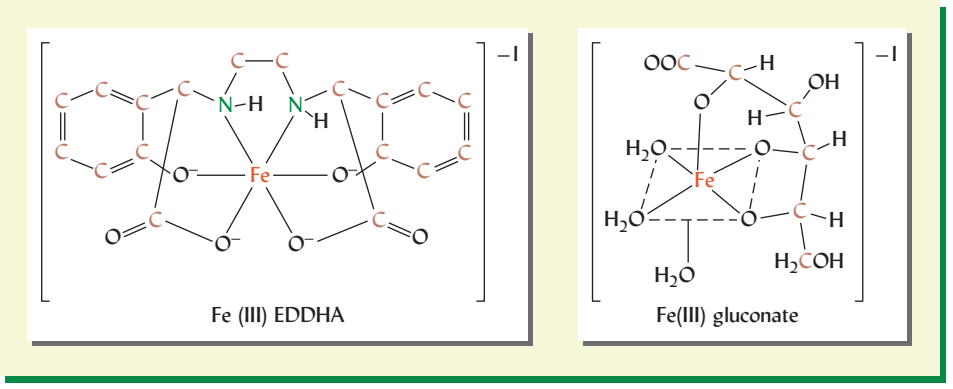

Figure 15.29 *Structural formula for two common iron chelates, ferric ethylendiamine di (o-hydroxyphenylacetic) acid (Fe-EDDHA) (a) and ferric gluconate (b). In both chelates, the iron is protected and yet can be used by plants.* (Diagrams courtesy of Ray R. Weil)

be synthesized by plant roots or microorganisms and released to the surrounding soil, may be present in the soil organic matter, or may be synthetic compounds in micronutrient fertilizers or added directly to the soil to enhance micronutrient availability. Iron, zinc, copper, and manganese are among the cations that form metal–chelate complexes. In their chelated form, the cations are protected from reaction with inorganic soil constituents that would cause them to form insoluble precipitates or otherwise make them unavailable for uptake by plants. Two examples of iron chelates are shown in Figure 15.29.

We will illustrate the effect of chelation using iron as an example. In the absence of chelation, when an inorganic iron salt such as ferric sulfate is added to a calcareous soil, most of the iron is quickly rendered unavailable (insoluble) by reaction with hydroxide, as follows:

$$\underset{\text{(available)}}{Fe^{3+} + 3OH^-} \rightleftharpoons \underset{\text{(unavailable)}}{FeOOH + H_2O} \qquad (15.3)$$

In contrast, if the iron is chelated, it largely remains in the chelate form, which is soluble and available for uptake by plants. In this reaction, the available iron chelate reactant is favored:

$$\underset{\text{(available)}}{\text{Fe chelate} + 3OH} \rightleftharpoons \underset{\text{(unavailable)}}{FeOOH + \text{chelate}^{3-} + H_2O} \qquad (15.4)$$

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The mechanism by which micronutrients form chelates are absorbed by plants is different for different plants. Many dicots appear to remove the metallic cation from the chelate at the root surface, reducing (in the case of iron) and taking up the cation while releasing the organic chelating agent in the soil solution. Roots of certain grasses have been shown to take in the entire chelate–metal complex, reducing and removing the metallic cation inside the root cell, then releasing the organic chelating agent back to the soil solution (Figure 15.30). In both cases, it appears that the primary role of the chelate is to allow metallic cations to remain in solution so they can diffuse through the soil to the root. Once the micronutrient cations are inside the plant, other organic chelates (such as citrates) may be carriers of these cations to different parts of the plant.

Stability of Chelates

Chelates vary in their stability and therefore in their suitability as sources of micronutrients for plants. The stability of a chelate is measured by its stability constant, which is related to the tenacity with which a metal ion is bound in the chelate. If the binding and release of a divalent metal by a chelating agent is represented by the following reaction

$$\text{Metal-chelate}^{-} \rightleftharpoons \text{metal}^{2+} + \text{chelate}^{3-} \tag{15.5}$$

then the stability constant K for the metal–chelate complex is calculated as follows, where the values in brackets are concentrations (e.g., mol/L) in solution:

$$K = \frac{[\text{metal-chelate}^{-}]}{[\text{metal}^{2+}][\text{chelate}^{3-}]} \tag{15.6}$$

The larger the stability constant, the greater the tendency for the metal to remain chelated. The stability constant K for each metal–chelate complex is different and is usually expressed as the logarithm of K (see Table 15.10).

The stability constants are given as logarithms, so a difference of 1.0 represents a tenfold difference in stability. Calcium, a macronutrient, is included because it is usually the metallic cation with by far the greatest activity in the soil solution and competes with micronutrient cations for binding sites in chelating agents. The relative cost of the chelating agents is also given.

The stability constant is useful in predicting which chelate is best for supplying which micronutrient. An added metal chelate must be reasonably stable within the soil if it is to have lasting advantage. For example, the stability constant (log K) for EDDHA-Fe^{3+} is 33.9, but

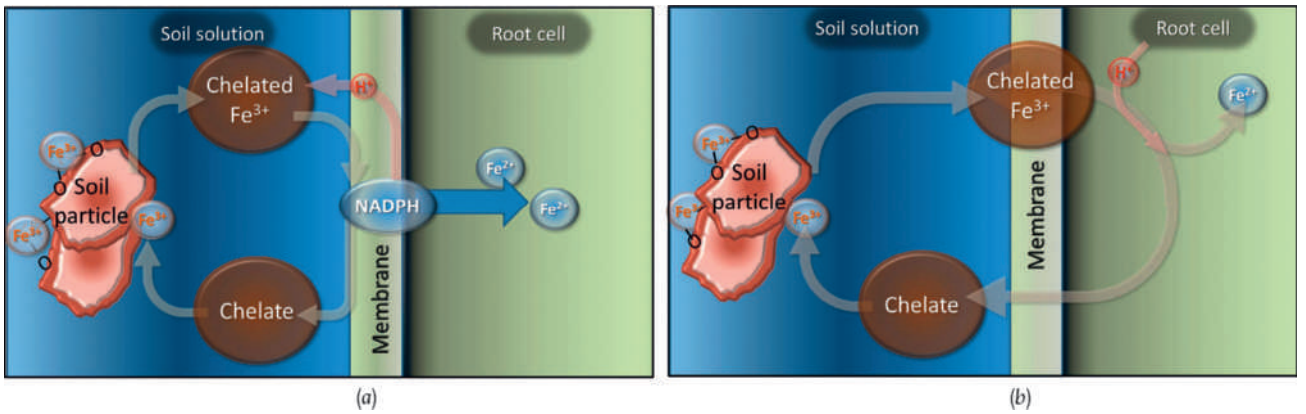

Figure 15.30 *Two ways in which plants utilize micronutrients held in chelated form.* (Left) *Most nongrass plants exude both H^+ ions to acidify the rhizosphere enough to solubilize Fe(III) and strong reducing agents (NADPH) to reduce iron to the more soluble Fe(II) at the outer surface of the root membrane. They then take in only the reduced iron, leaving the organic chelate in the soil solution where it can complex another iron atom.* (Right) *Grass plants* (Gramineae) *such as wheat or corn exude mugineic acids and similar chelating agents which then complex with iron in the rhizosphere. The roots then take the entire chelate–metal complex into their cells. Inside the cells, the iron is removed from the chelate and reduced to Fe(II) while the chelate is returned to the soil solution.* (Diagram courtesy of Ray R. Weil)

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Table 15.10
STABILITY CONSTANTS *K* FOR SELECTED CHELATING AGENTS AND NUTRIENT CATIONS
The stability constants are given as logarithms, so a difference of 1.0 represents a tenfold differ-ence in stability. Calcium, a macronutrient, is included because it is usually the metallic cation with by far the greatest activity in the soil solution and competes with micronutrient cations for binding sites in chelating agents. The cost of the chelating agents relative to gluconate is also given.

	log K[a]						
Chelating agent	Fe^{3+}	Fe^{2+}	Zn^{2+}	Cu^{2+}	Mn^{2+}	Ca^{2+}	Relative cost[b]
EDTA	25.0	14.27	14.87	18.70	13.81	11.0	4.5
EDDHA	33.9	14.3	16.8	23.94	—	7.2	45
HEEDTA	19.6	12.2	14.5	17.4	10.7	8.0	5.5
Citrate	11.2	4.8	4.86	5.9	3.7	4.68	—
Gluconate	37.2	1.0	1.7	36.6	—	1.21	1.0

[a] $K = \frac{[metal\text{-}chelate]}{[metal][chelate]}$

[b] Cost per kg of iron relative to the cost of iron gluconate. [Based on Clemens et al. (1990)]

that for EDDHA-Zn^{2+} is only 16.8. We can therefore predict that if EDDHA-Zn were added to a soil, the Zn in the chelate would be rapidly and almost completely replaced by Fe^{3+} from the soil:

$$\text{Zn chelate}^- + Fe^{3+} \rightleftharpoons \text{Fe chelate} + Zn^{2+} \tag{15.7}$$

Since the iron chelate is more stable than its zinc counterpart, the reaction goes to the right, and the released unchelated zinc ion is subject to precipitation reactions with the soil. Similarly, even though the stability constant for Ca chelates is generally low, in practice calcium often replaces micronutrients from chelates, because the concentration of Ca^{2+} in the soil solution is far greater than the concentrations of micronutrients.

It should not be inferred that chelates are effective only for iron. The chelates of other micronutrients, including zinc, manganese, and copper, are also used successfully to supply these nutrients. Apparently, replacement of the other micronutrients in the chelates by iron from the soil is sufficiently slow to permit plants to absorb the other added micronutrients. Also, because banded applications or foliar sprays are often used to supply zinc and manganese, the possibility of reaction of these elements in chelates with iron and calcium in the soil can be reduced or eliminated.

Chelates in Soil Ecology and Management

Chelating agents play important roles in soil ecology. Some plant species or strains are better adapted and more competitive than others in a low micronutrient soil because they can produce more effective chelating agents. An important objective of soil organic matter management is to encourage the formation of chelating agents during decomposition. Particularly intricate and interesting is the apparent ability of certain plants to preferentially stimulate certain soil bacteria which produce exceeding effective chelating agents termed siderophores. The siderophore molecules then capture and carry iron to the plant roots for uptake (Figure 15.31). A similar coordinated process also has been shown to occur with bacterial chelating agents specifically effective for zinc.

The use of synthetic chelates in industrial countries is substantial, in spite of the fact that they are quite expensive. They are most economical when used to ameliorate micronutrient deficiencies of such high-value plants as vegetables, fruit trees, and ornamentals. For most micronutrients application, chelates may not replace the less expensive methods of supplying as inexpensive inorganic sulfates, but they offer possibilities in special cases. Some of the chelators

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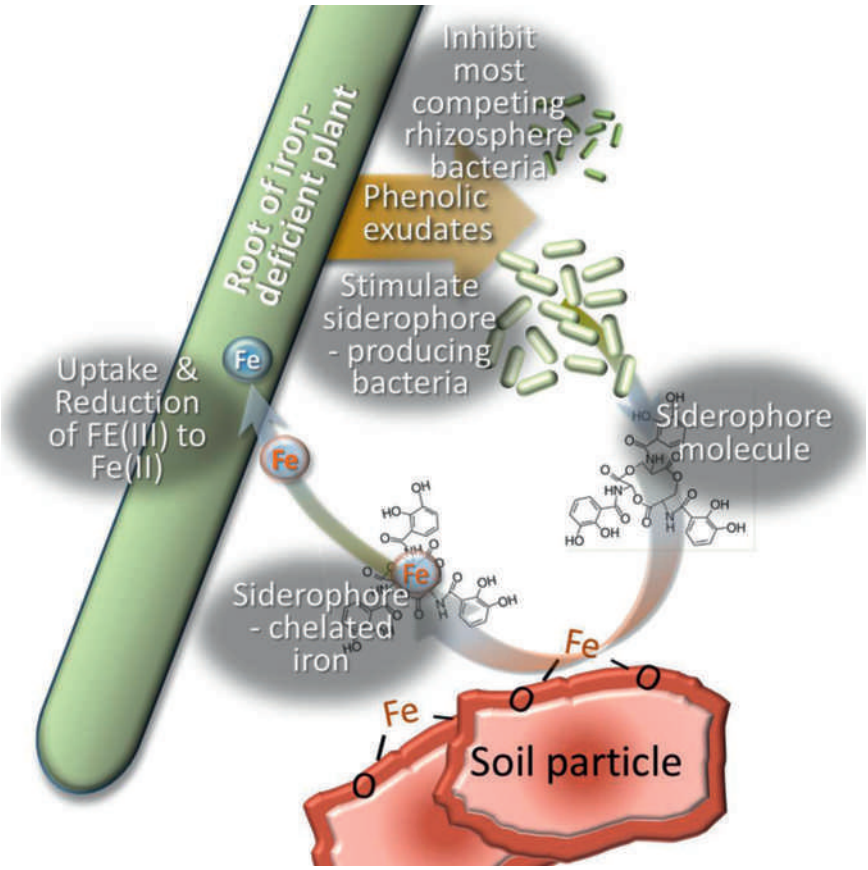

Figure 15.31 *When deficient in iron, certain plants can enlist specific rhizosphere ecosystem responses to iron deficiency by increasing root exudation of specialized phenolic compounds. These root exudates inhibit most of the competing rhizosphere bacteria while stimulating the growth only of certain bacteria that produce highly effective iron chelating agents termed siderophores. The siderophore molecules released by the favored bacteria capture and bond with Fe^{3+} ions in the immediate vicinity of the root surface, greatly enhancing the amount of iron available for plant uptake.* [Diagram courtesy of Ray R. Weil. Based on concepts in Jin et al. (2014)]

used in micronutrient fertilizers, such as gluconate, are naturally occurring and can supply certain micronutrients much more economically than the more expensive aminopolycarboxylate compounds (e.g., EDDHA) listed in Table 15.10. Research will likely continue to increase the opportunities for the effective use of chelates.

15.9 FACTORS INFLUENCING THE AVAILABILITY OF THE TRACE ELEMENT ANIONS

Unlike the cation micronutrients, the anion micronutrients seem to have relatively little in common with each other. Chlorine, molybdenum, and boron are quite different chemically, so little similarity would be expected in their reactions in soils. Arsenic and selenium, two other trace elements we will consider, also exhibit quite unique properties.

Chlorine

Chlorine (Cl) is commonly absorbed by plants in larger quantities than any of the micronutrients except iron. Most of the chlorine in soils is thought to occur in the form of the chloride ion, which leaches freely from humid-region soils. However, chlorination reactions carried out in plants and by microbes in soils can create organic chlorine compounds that may play a role in the chlorine nutrition of plants, especially forest trees. As much as 60% of the chlorine in forest soils has been shown to be in organic forms. Certain coniferous species, such as Norway spruce, and their rhizosphere microorganisms have been reported enhance the formation of organic chlorine and its rate of accumulation in forest soils.

In semiarid and arid regions, relatively high concentrations of Cl^- might be expected, with the amount reaching levels that may cause various negative effects and toxicities to plants. Accumulation of Cl^- (and other ions of dissolved salts) can be especially troublesome in

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poorly drained saline soils (see Section 10.3). In most well-drained areas, however, one would not expect high chlorine contents in the surface of arid-region soils unless unduly high levels of potassium chloride are applied as potassium fertilizer.

The plant-availability of Cl in soils is not hampered by any natural soil conditions, as is the case with the other micronutrients. Accretions of chlorine from the atmosphere (typical 5–10 kg/ha annually, but higher in coastal areas) are generally more than sufficient to meet most plant needs. However, in soils far from oceans mists and with very low levels of chloride, applications of this micronutrient anion (typically from fertilizer salts such as potassium chloride) have been shown to increase yields and alleviate foliar symptoms of Cl^- deficiency in wheat.

In most cases, where applications of chlorine produce beneficial effects on plant growth or health, the influence has been found to be indirect. Chlorine applications have helped to control several fungal diseases in plants, such as stalk rot in corn and "take all" in wheat. One of the indirect effects of chlorine on plant nutrition is its tendency to suppress nitrification and plant uptake of nitrate. This suppression leads to more NH_4^+ and less NO_3^- in the soil solution. The greater relative uptake of NH_4^+ ions, in turn, leads to a decrease in rhizosphere pH. This greater acidity increases the availability and uptake of manganese that may, in turn, suppress the "take all" disease. In other cases, apparent disease suppression may actually be a result of chloride's competitive reduction in plant nitrate uptake which, in turn, reduces the excessive nitrogen contents that can make plants more susceptible to fungal attack. In such cases, smaller applications of nitrogen might achieve the same reduction in disease severity, with the additional benefits of lower fertilizer costs and reduced nitrate susceptible to leaching loss.

Deficiency of chlorine does seem to directly affect the nutrition and health of some plants. For example, tropical palms, adapted to growth in coastal soils where ocean spray contributes much chlorine, sometimes show chlorine deficiency if they are grown on inland soils with relatively low chlorine levels.

Toxic effects of chlorine have also been noted. This element is an obligatory component of the most widely used potassium fertilizer, potassium chloride (also termed muriate of potash). Consequently, when high rates of potassium are required for optimum plant growth, equally high rates of chlorine are applied. Such high levels can be toxic to some plants, especially to those of the *Solonaceae* (tomatoes and the like) and *Leguminosae* (legumes such as clover, alfalfa, pea, bean, soybean) families. As a preventative measure, potassium sulfate may be used to supply most of any needed potassium, thereby avoiding difficulties from excess chlorine.

Boron

Boron (B) is one of the most commonly deficient of all the micronutrients. The availability of boron is related to the soil pH, this element being most available in acid soils. While it is most available at low pH, boron is also rather easily leached from acid, sandy soils. Therefore, although deficiency of boron is relatively common on acid, sandy soils, it occurs because of the low supply of total boron rather than because the boron present is not available.

In soils with more clay and oxides of iron and manganese, even if quite acid and sandy, boron is sorbed to mineral surfaces. This appears to significantly reduce the plant availability of the boron present. Such soils cover large areas of land in India. Crops there are commonly fertilized with boron to overcome yield-limiting deficiencies. Boron applied to these soils is of limited utility when sorption reactions reduce its availability in the soil solution. In some of these soils, organic matter can reduce the sorption by coating and masking the sorptive mineral surfaces. Thus, the role of soil organic matter in boron sorption can vary depending on the behavior of other constituents in the soil (Figure 15.32).

Boron deficiency is even more common at high pH levels—in both sandy soils (because of low boron content) and clayey soils (because the boron is tightly held by the clay). Soluble boron is present in soils mostly as boric acid [$B(OH)_3$] or as $B(OH)_4^-$. These compounds can exchange with mineral surface OH groups, forming difficult-to-reverse inner-sphere complexes (see Sections 8.7 and 8.11) on surfaces of iron and aluminum oxides and such silicate clays as kaolinite. Reactions such as the following take place:

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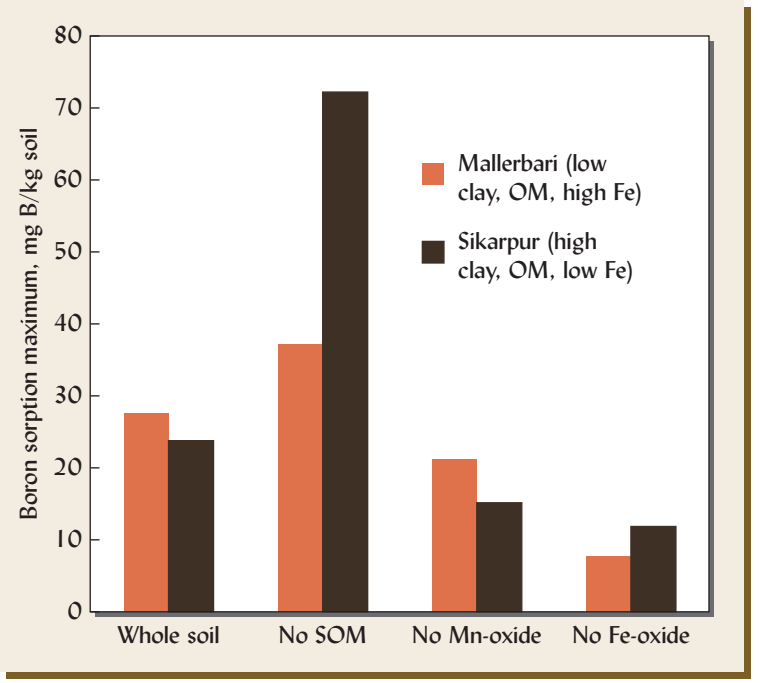
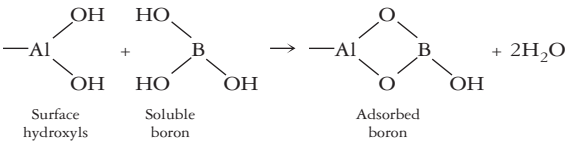


Figure 15.32 *Removal of soil organic matter and oxides of iron and manganese influences boron sorption from solution. However the influence of soil organic matter is not always consistent. The data here are for a two acidic (pH 4.8) Typic Fluvaquents in northern India. The Mallerbari soil had 12% clay, 1.2% organic C, 1.5% free iron oxides, while the Sikarpur soil had more clay (18%) and twice as much organic C (2.5%), but much lower free iron oxides content (0.01%). Maximum adsorption of B was measured in each soil after removal of the organic matter and the iron (and manganese) oxides and compared to B sorption in the untreated (whole) soils. Removal of organic matter, especially from the high organic C Sikarpur soil, greatly increased B sorption—probably because the organic matter had coated and masked the sorptive mineral surface of the clays and Fe- and Mn-oxides. Removal of Fe- and Mn-oxides, however, decreased the B sorption in both soils.* [Graphed from selected data in Sarkar et al. (2014)]



(15.8)

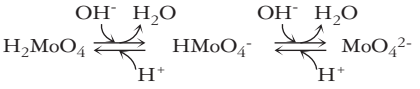
The boron so adsorbed is quite tightly bound, especially between pH 7 and 9 (Figure 15.33), the range of lowest availability of this element. In addition, plants tend to have a higher requirement for boron if calcium is abundant. These phenomena probably account for the lime-induced boron deficiency noted on some soils if their pH levels are raised to above 7.

At alkaline pH levels, boron is adsorbed by organic colloids with a binding strength even greater than that of inorganic colloids. On the other hand, boron is also a component of soil organic matter and is released by microbial mineralization. Consequently, organic matter serves as a major reservoir and source for boron in many soils and exerts considerable control over the availability of this nutrient.

Boron availability is impaired by long dry spells, especially following periods of optimum moisture conditions. This may be related to the fact that boron is generally taken up with the transpiration stream of water rather than by active ion transport, as is the case for uptake of most other nutrients. Dry conditions may also slow the mineralization of organically held boron. Boron deficiencies are also common in calcareous Aridisols and other soils with alkaline pH levels.

Molybdenum

Soil pH is the most important factor influencing the availability and plant uptake of molybdenum (Mo). The following equations show the forms of this element present at low pH (left) and high pH (right):



(15.9)

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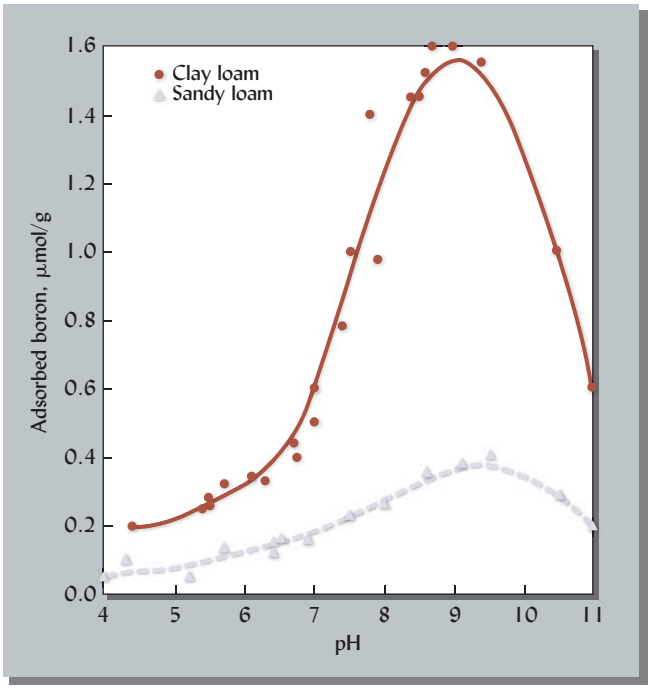
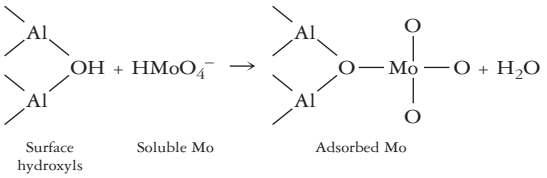


Figure 15.33 *Adsorption of boron increases as soil pH increases up to about 9. Boron is thought to form difficult-to-reverse (inner-sphere) complexes with hydroxyls on the surfaces of iron and aluminum oxides and silicate clays. Because of their greater surface area, fine-textured soils can tightly adsorb much more boron than can sandy soils, which may lose most of their boron by leaching. Therefore, boron deficiency is common at high pH in both sandy soils (because of low boron content) and in fine-textured clayey soils (because the boron is tightly held by the clay).* [Redrawn from Goldberg et al. (2000) and used with permission of the Soil Science Society of America]

At low pH values, the molybdenum is adsorbed by silicate clays and, more especially, by oxides of iron and aluminum through *ligand exchange* with hydroxide ions on the surface of the colloidal particles. Reactions such as the following occur:



(15.10)

The liming of acid soils will usually increase the availability of molybdenum. The effect is so striking that some researchers, especially those in Australia and New Zealand, argue that the primary reason for liming very acid soils is to supply molybdenum. Furthermore, in some instances 30 g or so of molybdenum added to a hectare of acid soils has given about the same increase in the yield of legumes as has the application of several megagrams of lime.

In acid soils, the high levels of sulfate may further reduce molybdenum uptake as the sulfate anion seems to compete with molybdenum at functional sites on plant metabolic compounds. On the other hand, the phosphate anion seems to improve the availability of molybdenum by competing for sorption sites on soil surfaces. For this reason, molybdate salts are often applied along with phosphate carriers to molybdenum-deficient soils. This practice apparently encourages the uptake of both elements and is a convenient way to add the extremely small quantities of molybdenum required. Legume seeds coated in a mixture of superphosphate and sodium molybdate have also been used successfully to add diverse forage plants, improving the grazing quality of acid-soil range and savanna lands. Interaction between molybdenum and phosphorus may exert a major influence on the productivity of tropical rainforests growing in acid soils because of the roles of both nutrients in the nonsymbiotic biological fixation process that provides the bulk of nitrogen for the forest growth (Figure 15.34).

Because molybdenum availability is high under alkaline conditions, in some arid regions molybdenum *toxicity* is a problem. The high solubility of molybdenum and low solubility of copper at high pH can combine to cause a disease known as molybdenosis, which interferes with

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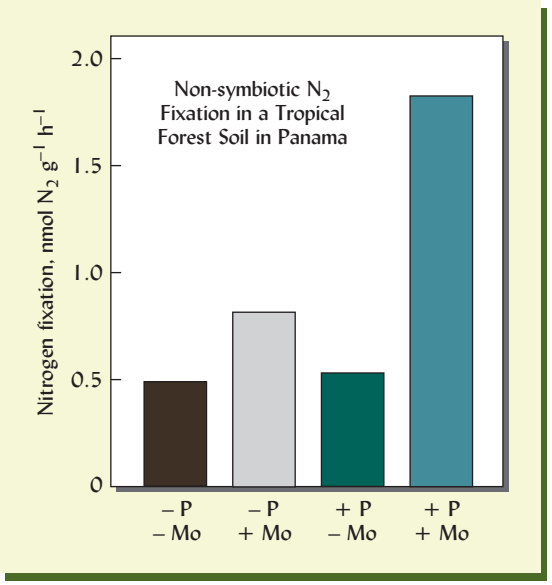

Figure 15.34 *Productivity and carbon sequestration in many tropical forests is largely dependent on nitrogen from nonsymbiotic biological N_2 fixation carried out by free-living soil bacteria in the surface soil horizons. Many scientists have observed that this critical process is often limited by the availability of phosphorus (P). But research in lowland tropical forests of Panama has shown that P stimulates N_2 fixation only when there is sufficient amounts of the micronutrient anion, molybdenum (Mo). In fact in all the sites studied in Panama, P additions stimulated N_2 fixation only if made in conjunction with Mo additions. The main sources of naturally occurring P and Mo in these soils are weathering minerals and dust deposition. Part of the problem is that in the O horizons where much of the N_2 fixation takes place, organic matter adsorbs MoO_4 in preference to H_2PO_4. This is an example of the complex interactions that can affect the necessary balance among plant nutrients in soils.* [Graphed from selected data in Wurzburger et al. (2012)]

normal copper assimilation. Ruminant animals (e.g., antelope, cattle, and sheep) grazing vegetation on high-molybdenum alkaline soils are most susceptible. Molybdenosis is most common on wet floodplains and alluvial fans in areas where alkaline soils formed from granite or shale parent materials.

Selenium

Although plants take up selenium (Se), it is not essential for plant growth. However, it is essential for human and animal health. This element also occurs in some soils at levels that are toxic both to plants and to animals that consume the plants. For example, excess selenium causes "blind staggers" in ruminants and embryonic deformities in waterfowl and mammals.[6] Natural selenium toxicities are found notably in soils developed on marine sedimentary parent material that is high in selenium. But human activities such as irrigation and mining can significantly increase the levels of selenium in soils, sometimes to toxic levels.

Selenium is found in nature in four major solid forms and several volatile forms. The degree of toxicity is much more dependent on the particular forms present than on the total amount of selenium in the soil. The following reactions illustrate the microbiological reduction of the soluble and highly oxidized selenates to reduced and less soluble forms[7]

$$\underset{\substack{\text{[Se(VI)]}\\ \text{Selenate}}}{SeO_4^{2-}} \rightleftharpoons \underset{\substack{\text{[Se(IV)]}\\ \text{Selenite}}}{SeO_3^{2-}} \rightleftharpoons \underset{\substack{\text{[Se(0)]}\\ \text{Elemental selenium}}}{Se} \rightleftharpoons \underset{\substack{\text{[Se(-II)]}\\ \text{Selenide}}}{Se^{2-}} \rightleftharpoons \underset{\substack{\text{[Se(-II)organic]}\\ \text{Dimethyl selenide}}}{(CH_3)_2Se} \tag{15.11}$$

Similar to sulfur, selenium is found in four oxidation states in soils: 2–, 0, 4+, and 6+. The particular compounds present at any one time are determined largely by factors such as redox potential, pH, organic ligands present, and the activities of soil microorganisms. Selenates are most soluble and are prominent in well-aerated soils, especially if the pH is high (above 7). They seem to be responsible for most environmental selenium toxicity. Selenites are commonly dominant under acid (pH 4.5–6.5), poorly drained conditions, but are only slowly available

[6]Selenium famously caused birth defects in waterfowl in California (see Box 10.3) and in race horses in a popular mystery thriller novel (Francis, 1982).

[7]Nonbiological reduction of selenates also occurs in the presence of ferrous/ferric hydroxide $[Fe(II)_aFe(III)_b(OH)12]$ $X \cdot 3H2O$; where $a = 1 - 4$, $b = 1 - 2$, and X = an anion, such as SO_4^{2-}, a compound known as *green rust*, commonly found in wet soils. See Myneni et al. (1997).

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since they are adsorbed by iron oxides. If added to soils to enhance the selenium contents of crops they will not likely induce selenium toxicities.

Elemental selenium and selenides are quite insoluble and accumulate in wetland sediments, as do some Se-organic compounds. Some plants, in association with fungi and bacteria, absorb both organic and inorganic forms of selenium and produce volatile organics such as dimethyl selenide and dimethyl diselenide that can be released as gases to the atmosphere. These are relatively nontoxic compounds. As explained in Box 15.2, these reactions are used as a promising means of **bioremediation** to remove toxic levels of soluble selenium from soils and water (see also Box 10.3 and Section 18.5).

Arsenic[8]

A number of other trace elements found in the anionic form have been reported to be essential for either plants or animals, but we will consider only arsenic because of its toxic effects on humans and other animals. This element is a common natural constituent of soils, but its level is augmented in some cases by human activities. For example, it has been widely used as a pesticide and can be leached from certain mine tailings.

BOX 15.2

SELENIUM—BOUND AND VAPORIZED[a]

Irrigation waters carry two relatively soluble forms of selenium, selenates [$Se(VI)O_4^{2-}$] and selenites [$Se(IV)O_3^{2-}$]. When selenium first moves into the soil, some of it is reduced quickly to very insoluble elemental selenium (Se^0), which is largely unavailable to plants and therefore is nontoxic. Further transformations take place as both soluble forms move downward into the soil (Figure 15.35). Reducing conditions favor formation of selenites, which tend to be tightly sorbed by iron oxides. Further reduction induced by microbes leads to the formation of not only elemental selenium [Se^0] but to selenides [Se^{2-}], both of which are quite insoluble. Thus, reducing conditions encourage the formation of insoluble forms, thereby lowering the toxicity of the selenium present.

As microbes and plants metabolize selenium, it is assimilated into organic forms such as selenoamino acids and selenoproteins, most of which are also quite insoluble. Certain plant species such as rice and members of the *Brassica family* (generally in association with soil fungi and bacteria) are able to attach methyl groups (methylation) to organoselenium compounds, thereby forming volatile gases such as dimethylselenide (DMSe). DMSe is 700 times less toxic than the selenates and can be dispersed into the atmosphere without any environmental damage. The process seems to work best in soils that are moist but not flooded and that are well supplied with organic materials to provide metabolic energy for these reactions. To allow continued irrigated crop production without damaging the environment, soil scientists are working to harness both pathways for selenium detoxification—the process that changes selenium to insoluble forms and the process that releases the selenium into the atmosphere.

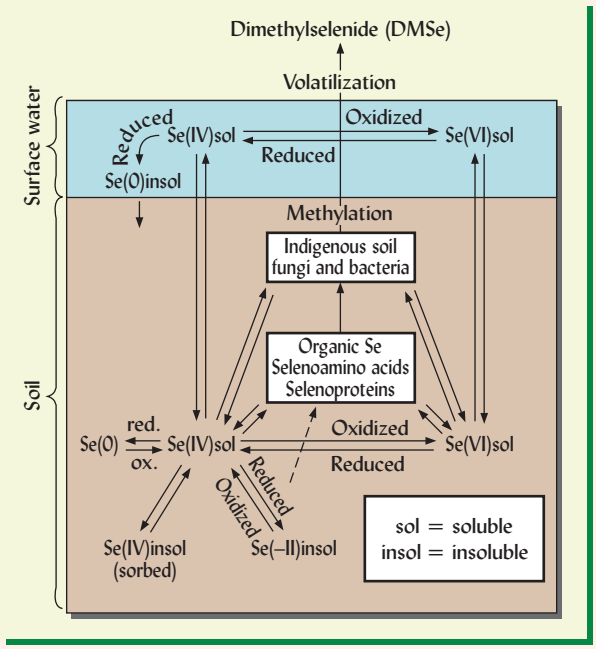

Figure 15.35 *Selenium transformation in wetland soils.* (Diagram courtesy of N. C. Brady)

[a]Concepts for the diagram are from Hayes and Traina (1998) and Frankenberger and Losi (1995). An excellent review of research on phytovolatilization of selenium is found in Zayed et al. (2000).

[8]For a comprehensive treatment of the chemistry and management of arsenic in the environment, see Naidu et al. (2006); for a review of the serious problem of arsenic in soils and groundwater in Bangladesh, see Hossain (2006).

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For centuries, arsenic has been known and used as a human and animal poison. Its presence in soils, groundwater, and well water is of concern to people around the world, but especially in Bangladesh, India, China, Chile, and Slovakia. In Bangladesh, for example, more than 20 million people (about 15% of the country's population) are believed to be drinking arsenic-contaminated water containing more than 50 ppb As. Thousands are suffering from skin cancer that is caused by naturally occurring arsenic toxicity. The well water in the United States is generally safe, but the arsenic content of some wells in arid western states exceeds the current 5 ppb maximum contaminant level (MCL) standard promulgated by both the U.S. EPA (post-2006) and the World Health Organization as the level above which human health is at risk.

Arsenic is found as a minor constituent of many minerals (especially sulfides). Upon their breakdown it becomes associated with the soil in two major forms, arsenite [AsO_3^{3-}, or three-valent As(III)] and arsenate (AsO_4^{3-}, or five-valent As(V)]. Both forms are sorbed by oxides and hydroxides of iron, but As(V) is generally more strongly sorbed, especially in acid soils. Consequently, arsenites [As(III)] are generally more mobile and move more easily into groundwater, the source of drinking water in many parts of the world. For this reason, wet and reduction-prone conditions are to be avoided to minimize dissolution and movement of the most toxic forms of arsenic.

Scientists are evolving methods for the remediation of arsenic-contaminated waters. For example, they are trying to use hydrous oxides of iron as sorbing agents for the arsenic in drinking water. Also, they have discovered that certain plants are *hyperaccumulators* of arsenic. For example, an uncultivated fern is known to have accumulated as much as 2% arsenic in research plots in Florida, USA. By growing and harvesting such plants, it may be possible to reduce the level of soluble arsenic in the soils and the groundwater.

15.10 SOIL MANAGEMENT AND TRACE ELEMENT NEEDS

Balance among the trace elements is as essential as, but even more difficult to maintain than, macronutrient balance. Some of the plant enzyme systems that depend on micronutrients require more than one element. For example, both manganese and molybdenum are needed for the assimilation of nitrates by plants. The beneficial effects of combinations of phosphates and molybdenum have already been discussed. Apparently, some plants need zinc and phosphorus for optimum use of manganese. The use of boron and calcium depends on the proper balance between these two nutrients. A similar relationship exists between potassium and copper and between potassium and iron in the production of good-quality potatoes. Copper utilization is favored by adequate manganese, which in some plants is assimilated only if zinc is present in sufficient amounts. Ruminant animals fed plant tissue with low Cu/Mo ratios suffer molybdenum toxicity. Of course, the effects of these and other nutrients will depend on the specific plant being grown, but the complexity of the situation can be seen from the examples cited.

Antagonism and Synergism

Some enzymatic and other biochemical reactions requiring a given micronutrient may be poisoned by the presence of a second trace element in toxic quantities. Other negative effects occur because one element competes with or otherwise reduces uptake of a second element by the plant root. On the other hand, a good supply of a certain nutrient may enhance the utilization of a second nutrient element in what is termed a *synergistic effect.* Some of these interactions are summarized in Table 15.11.

Some of the *antagonistic* effects may be used effectively in reducing toxicities of certain of the micronutrients. For example, copper toxicity of citrus groves caused by residual copper from fungicidal sprays may be reduced by adding iron and phosphate fertilizers. Sulfur additions to calcareous soils containing toxic quantities of soluble molybdenum may reduce the availability, and hence the toxicity, of molybdenum. The hyperaccumulation of phosphorus, manganese, and magnesium in zinc-deficient plants is an example of the complex interactions among essential elements as they influence plant nutrition.

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Table 15.11
SOME ANTAGONISTIC (NEGATIVE) AND SYNERGISTIC (POSITIVE) EFFECTS OF OTHER NUTRIENTS ON MICRONUTRIENT UTILIZATION BY PLANTS
The occurrence of so many interactions emphasizes the need for balance among all nutrients and avoidance of excess application of any particular nutrient.

	Elements decreasing utilization		Elements increasing utilization	
Micronutrient	Soil and root surface reactions	Plant metabolic reactions	Soil and root surface reactions	Plant metabolic reactions
Fe	B, Cu, Zn, Mo, Mn	Mn, Mo, P, S, Zn	B, Mo	
Mn	Fe, B	Fe	B	
Zn	Mg, Cu, B, Fe, P	Fe, N, Mg	N, B	Fe
Cu	B, Zn, Mo	P, N	B	
B	Ca, K			N
Mo	S, Cu	S	P	P
Ni	Ca, Fe	Fe, Zn		

These examples of nutrient interactions, both positive and negative, emphasize the highly complicated nature of the biological transformations in which micronutrients are involved. The total agricultural area on which micronutrient imbalances require special treatment is increasing as soils are subjected to more intensive cropping methods.

Before leaving the topic of nutrient balance and imbalance, it should be noted that human activities from mining to industrial spills can contaminate soils with high levels of micronutrients (as well as non-nutrient metals) that threaten to be toxic to plants, animals, fish, and/or people. In Chapter 18 (Sections 18.7 and 18.8) we will address the remediation of such contaminated land, including bioremediation using special plants that can accumulate the offending metals in their tissues for removal from the soil.

In diagnosing the cause of plant abnormalities, one should keep in mind the conditions under which micronutrient deficiencies or toxicities are likely to occur. Sandy soils, Histosols, and soils having very high or very low pH values are prone to micronutrient deficiencies. Intensive cropping and heavy macronutrient fertilization may increase the likelihood of soils becoming deficient in micronutrients. Although the characteristics of each micronutrient are quite specific, we can make the following generalizations with respect to managing micronutrients in soils.

Changes in Soil Acidity

In very acid soils, one might expect toxicities of iron and manganese and deficiencies of phosphorus and molybdenum. These can be corrected by liming and by appropriate fertilizer additions. Alkaline soils may have deficiencies of iron, manganese, zinc, and copper and, in a few cases, a toxicity of molybdenum.

No specific statement can be made concerning the pH value most suitable for all the elements. However, medium-textured soils generally supply adequate quantities of micronutrients when the soil pH is held between 6 and 7. In sandy soils, a somewhat lower pH may be justified because the total quantity of micronutrients is low, and even at pH 6.0, some cation deficiencies may occur. It is important to be on guard to recognize inadvertent increases in soil pH, such as those occurring from application of lime-stabilized sewage sludge (see Chapter 16) or leaching of calcareous gravel and pavements.

Soil Moisture

Drainage and moisture control can influence micronutrient solubility in soils. Improving the drainage of acid soils will encourage the formation of the oxidized forms of iron and manganese.

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These are less soluble and, under acid conditions, less toxic than the reduced forms. Flooding a soil will favor the reduced forms of iron and manganese, which are more available for plant uptake (Figure 15.36). Excessive moisture at high pH values can have the opposite effect since poorly drained soils have a high carbon dioxide concentration, encouraging the formation of bicarbonate ions, which reduces iron availability. Poor drainage also increases the availability of molybdenum in some alkaline soils to the point of producing plants with toxic levels of this element.

Fertilizer Applications

Micronutrient deficiencies are relatively unlikely to be a problem in most soils to which plant residues are returned and organic amendments, such as animal manure or sewage sludge, are regularly applied. Animal manures applied at normal rates sufficient to supply macronutrient needs carry enough copper, zinc, manganese, and iron to supply a major portion of micronutrient needs as well (see Table 16.9). In addition, the chelates produced during manure decomposition enhance the availability of these micronutrients.

The most common management practice to overcome micronutrient deficiencies (and some toxicities) is the use of commercial fertilizers, applied alone or in conjunction with organic amendments and manipulation of soil pH and drainage. Examples of fertilizer materials are listed in Table 15.12 and typical rates of application to soil are given in Table 15.13. Micronutrient fertilizers are most commonly applied to the soil, although foliar sprays and even seed treatments can be used. Foliar sprays of dilute inorganic salts or organic chelates are more effective than soil treatments where soil pH and other factors would render the soil-applied nutrients unavailable.

For soil applications, about one-half to one-fourth as much fertilizer is needed if the application is banded rather than broadcast (see Figure 16.30). About one-fifth to one-tenth as much fertilizer is needed if the material is sprayed on the plant foliage. Foliar application may, however, require repeated applications in a single year. Treating seeds with small dosages (20–40 g/ha) of molybdenum has had satisfactory results on molybdenum-deficient acid soils.

The micronutrients can be applied to the soil either as separate materials or incorporated in standard macronutrient carriers. Unfortunately, the solubilities of copper, iron, manganese, and zinc can be reduced by such incorporation, but boron and molybdenum remain in reasonably soluble condition. Liquid macronutrient fertilizers containing polyphosphates encourage the formation of complexes that protect added micronutrients from adverse chemical reactions. In effect, polyphosphates in fertilizer solutions act as chelating agents for micronutrients. High-surface-area pitted glasslike beads, called **frits**, are manufactured with boron, copper, zinc, and other micronutrients incorporated into the glass. These fritted materials slowly release their micronutrients as the glass weathers in the soil. This slow release avoids some of the problems of precipitation and sorption that might otherwise occur, particularly in an alkaline soil.

Figure 15.36 *Manganese toxicity in young cotton plants as affected by soil moisture during the three weeks prior to planting the cotton seed. The crinkled-leaf symptom and stunted size resulted from toxic levels of manganese in the soil that had been flooded prior to planting. Both pots were maintained at field-capacity water content from sowing to harvest. The Jackland soil (Aquic Hapludult) used is high in manganese-containing minerals and has a pH of approximately 5.8.* [Details in Weil et al. (1997), photo courtesy of Ray R. Weil]

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Table 15.12
A Few Commonly Used Fertilizer Materials That Supply Micronutrients

Micronutrient	Commonly used fertilizers		Nutrient content, %
Boron	Borax	$Na_2B_4O_7 \cdot 10H_2O$	11
	Sodium pentaborate	$Na_2B_{10}O_{16} \cdot H_2O$	18
Copper	Copper sulfate	$CuSO_4 \cdot 5H_2O$	25
Iron	Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	19
	Iron chelates	NaFeEDDHA	6
Manganese	Manganese sulfate	$MnSO_4 \cdot 3H_2O$	26–28
	Manganese oxide	MnO	41–68
Molybdenum	Sodium molybdate	$Na_2MoO_4 \cdot 2H_2O$	39
	Ammonium molybdate	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	54
Zinc	Zinc sulfate	$ZnSO_4 \cdot H_2O$	35
	Zinc oxide	ZnO	78
	Zinc chelate	$Na_2ZnEDTA$	14

Selected from Murphy and Walsh (1972).

Economic responses to micronutrients are becoming more widespread as intensity of plant production and our knowledge about micronutrients increases. In high-value ornamental horticulture and turfgrass management, a small application of a micronutrient such as manganese can sometimes serve as a very inexpensive and environmentally friendly means of controlling plant disease (Figure 15.37). Profitability is also seen in the yield and quality responses to micronutrients by fruits, vegetables, and field crops in areas of neutral to alkaline soils. Even on acid soils, deficiencies of these elements are increasingly encountered. Molybdenum, which has been used for some time for forage crops and for cauliflower and other vegetables, has received attention in recent years for forest nurseries and soybeans, especially on acid soils. Micronutrients have been used for decades in plant production on muck soils and on very sandy soils. To maintain optimal plant production, the use of micronutrients will be increasingly common under many other types of soil conditions, such as those previously mentioned.

A soil will often produce a micronutrient deficiency in some plants but not in others (see, e.g., Figure 15.12*c*). Plant species, and varieties within species, differ widely in their susceptibility to micronutrient deficiency or toxicity. Table 15.13 provides examples of plant species known to be particularly susceptible or tolerant to several micronutrient deficiencies.

Marked differences in crop needs for micronutrients make fertilization a problem where rotations are being followed. On general-crop farms, vegetables are sometimes grown in rotation with small grains and forages. If the boron fertilization is adequate for a vegetable crop such as red beets, or even for alfalfa, the small-grain crop grown in the rotation may show toxicity damage. These facts emphasize the need for specificity in determining crop nutrient requirements and for care in meeting these needs.

Plant Selection and Breeding[9]

Variation in plant abilities to accumulate micronutrients and other trace elements suggests that plant selection and breeding may hold potential for overcoming deficiencies and toxicities of these elements. For example, some species in the *Brassicaceae* family are able to accumulate 5–100 times as much of certain trace metals as found in most other plants. Similarly,

[9]For a review of human health impacts of micronutrient deficiencies, see Stein et al. (2010).

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Table 15.13
PLANTS KNOWN TO BE ESPECIALLY SUSCEPTIBLE OR TOLERANT TO, AND SOIL CONDITIONS CONDUCIVE TO, MICRONUTRIENT DEFICIENCIES

Plants which are most susceptible to deficiency of a micronutrient often have a relatively high requirement for that nutrient and may be relatively tolerant to levels of that nutrient that would be high enough to cause toxicity to other plants.

Micro-nutrient	Common rates recommended for soil application,[a] kg/ha	Plants most commonly deficient (high requirement or low efficiency of uptake)	Plants rarely deficient (low requirement or high efficiency)	Soil conditions commonly associated with deficiency
Iron	0.5–10.0	Blueberries, azaleas, roses, holly, grapes, oaks, nuts, maple, bean, sorghum,	Wheat, alfalfa, sunflower, cotton	Calcareous, high pH, waterlogged alkaline soils
Manganese	2–20	Peas, oats, apple, sugar beet, raspberry, citrus	Cotton, soybean, rice, wheat	Calcareous, high pH, drained wetlands, low organic matter, sandy soils
Zinc	0.5–20	Corn, onion, pines, soybeans, beans, pecans, rice, peach, grapes	Carrots, asparagus, safflower, peas, oats, crucifers, grasses	Calcareous soils, acid, sandy soils, high phosphorus
Copper	0.5–15	Wheat, corn, onions, citrus, lettuce, carrots	Beans, potato, peas, pasture grasses, pines	Histosols, very acid, sandy soils
Boron	0.5–5	Alfalfa, cauliflower, celery, grapes, conifers, apples, peanut, beets, rapeseed, pines	Barley, corn, onion, turfgrass, blueberry, potato, soybean	Low organic matter, acid, sandy soils, recently limed soils, droughty soils, soils high in 2:1 clays
Molybdenum	0.05–0.5	Alfalfa, sweet clover, crucifers (broccoli, cabbage, etc.), citrus, most legumes	Most grasses	Acid sandy, weathered soils with amorphous Fe and Al

[a]The lower end of each range is typical for banded applications; the higher end is typical for broadcast applications.

black gum (*Nyassa sylvatica*) is an accumulator of cobalt. *Bioremediation* may take advantage of such accumulators in removing toxic quantities of some trace elements from polluted soil (see Section 18.5). Human nutrition and health are also affected by the trace element content of plants used as food. Some recent research suggests that plant breeding and biotechnology may be used to select and/or create plant varieties that more efficiently absorb trace elements or that tolerate their toxic levels in soils.

Fighting Micronutrient Hunger[10]

Worldwide, malnutrition is a leading contributor to human illness and micronutrient deficiencies, in particular, pose serious human health concerns. Iron deficiency anemia has been estimated to be among the top global ten health burdens, debilitating 3–5 billion people. Human deficiencies of zinc and copper are also widespread, afflicting perhaps a billion people. In large parts of Europe and Asia, the Se in peoples' diets is also below the needed levels. In many cases these deficiencies stem from a lack of diversity—especially of animal products and green

[10]For an assessment of global human health problems, including micronutrient deficiencies, see The World Bank (2013); for an evaluation of research strategies to determine changes in nutrient density of crops, with an emphasis on vegetable, see Farnham and Grusak (2014).

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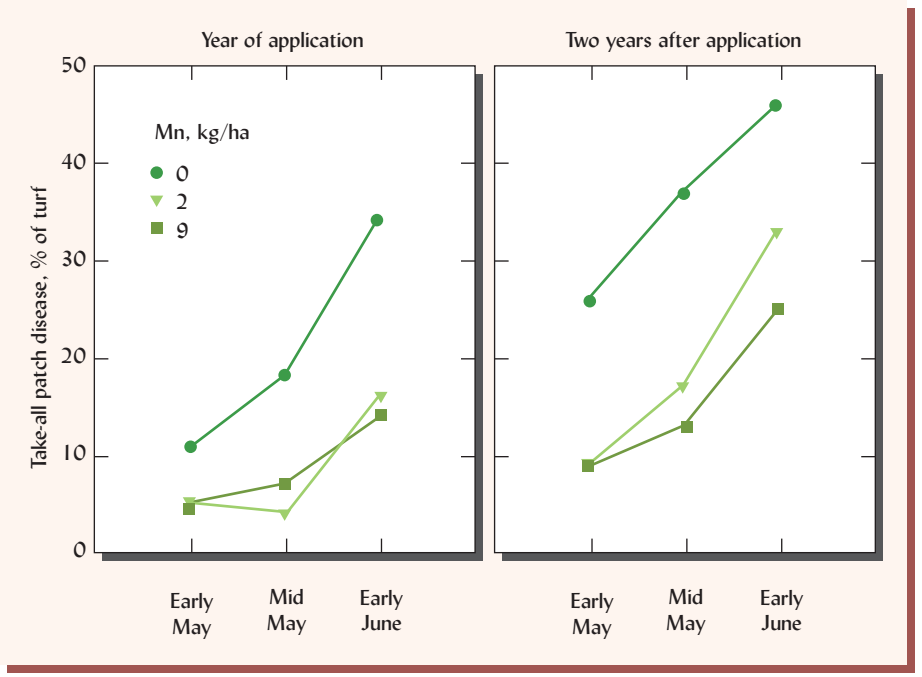

Figure 15.37 *Manganese application controls take-all patch disease if the soil pH is kept low enough for Mn to remain readily available. Just 2 kg/ha of Mn significantly reduced the disease severity in a bentgrass turf in this study. The effects remained even two years after the application. However, applications 12–18 months apart are recommended for acceptable control. The disease is named "take-all" because of total destruction of the plant by the fungal pathogen* Gaeumannomyces gramini. *This pathogen also causes take-all disease of wheat, another member of the grass family. It is thought that improved Mn nutrition enhances lignin biosynthesis in the plant cell walls, making them more resistant to attack (see also Table 15.8).* [Drawn from data in Heckman et al. (2003). Diagrams courtesy of Ray R. Weil]

vegetables—in the diets of people who rely upon staple grain products made from rice, wheat, or corn for most of their nutrition.

Aside from serious nutritional concerns about diets lacking in diversity or based on highly refined foods from which nutrients have been removed by processing, nutritionists have raised concerns that today's crops may be less "nutrient dense" (i.e., contain lower concentrations of nutrient elements) than crops grown in the past. Concentrations of such micronutrients as copper, zinc, and iron in many foods today have been found to be lower than those reported a half century ago. Some suggest that the cause of declining micronutrient density in crops is the depletion of soil nutrients by intensive farming, especially the use of mineral fertilizers that stimulate high yields but supply only macronutrients, not micronutrients. Careful research, however, suggests that any declines that have occurred resulted more from changes in grain crop genetic (varieties) than from soil depletion (Table 15.14). Lower micronutrient concentrations in grain may owe partially to similar amounts of micronutrient taken up being diluted in a higher yield of grain, and partially to some loss of micronutrient accession traits through genetic selection that focused on increasing grain yield.

Although plants exert considerable control over the uptake of nutrients such as Fe, Zn, and Cu (see Sections 15.8), the influence of soil properties is still significant. In the case of Se (see Section 15.9), soil chemistry seems to have an even greater influence, as plants exert little control over the uptake of this element, which though apparently not needed by the plant, is essential for animals (Table 15.15). Plants may easily take up levels of Se ranging from so low that people and animals may suffer deficiency to so high that animals may succumb to toxicity (see Box 15.2). The Se content of wheat used to make bread is of major importance to human health, as Se is essential for all animals and at relatively high levels may even reduce the incidence of some cancers. Some species of *Astragalus* and *Stanleya* are used as dietary supplements as they can accumulate about five times as much selenium as do cereal crops grown in similar soils.

World political leaders have turned to plant scientists to create rice varieties that are both high-yielding and high in iron that is readily assimilated by humans. Some progress has been made in improving the iron content of rice by using conventional plant-breeding techniques, and studies show the potential for even greater progress by using biotechnical methods. However, there is evidence that plant breeders have inadvertently selected for cultivars that, while high yielding, may be less effective in taking up trace elements important in

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Table 15.14
CHANGES IN ZINC AND COPPER CONTENTS OF SOIL AND HARVESTED GRAIN DURING 160 YEARS OF CONTINUOUS WHEAT FARMING IN ENGLAND[a]

In the post-1960s era micronutrient concentrations in the wheat grain declined significantly. The concentrations of micronutrients in the soil did not decline where fertilizer only was used. Where farmyard manure (a good source of micronutrients) was used the levels in the soil were significantly higher post-1960s and increased during the period. The researchers concluded that the decline in wheat "nutrient density" was a result of genetic changes in the "green revolution era" high-yielding, short stem wheat varieties grown in the most recent four decades, rather than resulting from soil depletion.

	Concentration in wheat grain harvested				Concentration in soil sampled			
	Zinc		Copper		Zinc		Copper	
Historical period:	1845–1967	1968–2005	1845–1967	1968–2005	1845–1920	1965–2005	1845–1920	1965–2005
Soil amendments used	mg/kg							
Farm yard manure	37	27	5.4	4.0	60	90	16	22
Mineral fertilizer (N, P, K, Mg, S)	32	22	5.0	3.6	57	70	15	17

[a]Based on data selected or extrapolated from Fan et al. (2008).

Table 15.15
EFFECT OF SOILS ON THE CONCENTRATIONS ($\mu g\ g^{-1}$) OF FOUR ELEMENTS IMPORTANT AS MICRONUTRIENTS FOR HUMANS IN HARD RED WINTER WHEAT USED FOR MAKING BREAD

For each location, the mean and the range of values for 14 different wheat cultivars is given. For the three plant nutrients (Fe, Zn, and Cu), the variations among cultivars and between soils were relatively small, but for Se (not a plant nutrient), values differed almost tenfold between soils and much less among plant cultivars. The newer, higher-yielding cultivars in this study tended to have the lower values within each range.

	Hutchinson, KS		Manhattan, KS	
Element	Mean	Range	Mean	Range
Fe	31.4	24.4–42.8	33.7	30.2–38.3
Zn	20.9	16.0–26.3	29.3	26.1–33.9
Cu	2.12	1.74–2.82	4.2	3.68–5.68
Se	0.36	0.28–0.48	0.05	0.04–0.06

From Garvin et al. (2006). Copyright of Society of Chemical Industry. Reproduced with permission granted by John Wiley & Sons, Ltd. on behalf of SCI.

human diets (Table 15.15). Similar differences exist in genetic tolerance of plants to nutrient deficiencies. The future calls for close collaboration between soil scientists, plant geneticists, and human nutritionists in exploring the long-term health and sustainable development implications of these findings.

Global Management Issues

Trace element deficiencies and toxicities have been diagnosed in most areas of crop production and some forest areas of Europe and the United States. However, in some developing

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countries, particularly in the tropics, the extent of these deficiencies is much less well known. Recent research suggests that crop deficiencies in zinc, boron and, to a lesser degree, copper are common on highly weathered soils in the humid and subhumid tropics. Irrigation schemes that bring calcareous soils in desert areas under cultivation are often plagued with deficiencies of iron, zinc, copper, and manganese. As macronutrient deficiencies are addressed and yields are increased, more micronutrient deficiencies will undoubtedly come to the fore. One encouraging factor is the small quantity of micronutrients usually needed, making it relatively easy to add these nutrients to fertilizer materials without significantly increasing the transport costs of the macronutrient fertilizers already being shipped to remote parts of the world. The management principles established for the economically developed countries should also be helpful in alleviating micronutrient deficiencies in less-developed countries. Sustainable solutions are most likely to be achieved by simultaneous application of multiple soil and plant management strategies for enhancing plant utilization of micronutrient resources (Table 15.16).

15.11 CONCLUSION

Calcium and magnesium are macronutrients usually used in quantities similar to sulfur and phosphorus. However, for woody plants and for certain "calcicole" plants, calcium is used in amounts that rival nitrogen and potassium (1–3% Ca in the dry matter). Both Ca and Mg are intimately associated with the processes of soil acidification and neutralization and thus are linked to sulfur and nitrogen deposition. The cycling of these two nonacid cations is of major concern in biogeochemistry and soil Ca supplies greatly impact the nature of the ecology that will develop in an area. Calcium and magnesium also impact global carbon balance through the precipitation and dissolution of Ca and Mg carbonates.

Silicon is an important element taken up and used by most plants in macronutrient-like quantities, but not generally considered to be an essential nutrient element. Despite its occurrence in large quantities in most soils, plants often respond positively to its application in the more soluble forms. Silicon appears to help plant resist attacks by pest and pathogens and to grow better under conditions of environmental stress.

Micronutrient availability often regulates plant species competition and survival on a site. Micronutrients are becoming increasingly important to world agriculture as crop removal of these essential elements increases. Soil and plant tissue tests confirm that these elements are limiting crop production over wide areas and suggest that attention to them will likely increase in the future.

Table 15.16
SOIL- AND PLANT-BASED STRATEGIES FOR ENHANCING MICRONUTRIENT UPTAKE[a]

Soil management	Plant management
• Root zone fertilization – Soil pH regulation by amendment with lime or sulfur. – Regulation of rhizosphere pH by ratio of NO_3^- to NH_4^+ supplied – Bacterial inoculants (iron-reducing bacteria, etc.) – Banding inorganic salt or chelated micronutrient • Soil water/aeration management • Enhanced soil organic matter by use of cover crops, reduced tillage, and organic amendments	• Foliar spray of dilute inorganic micronutrient salts or chelates • Injection of micronutrient solution into plant stem/trunk • Genetic improvement for enhanced uptake efficiency • Interplanting with other species, e.g., dicot/grass intercropping • Choice of species or strain adapted to efficient micronutrient uptake at existing soil pH

[a]Generalized from concepts regarding iron deficiency in Zuo and Zhang (2011).

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Micronutrient deficiencies are due not only to low contents of these elements in soils but more often to their unavailability to growing plants. They are adsorbed by inorganic constituents such as Fe, Al oxides and form complexes with organic matter, some of which are only sparingly available to plants. Other such organic complexes, known as *chelates*, protect some of the micronutrient cations from inorganic adsorption and make them available for plant uptake.

Toxicities of micronutrients retard both plant and animal growth. Removing these elements from soil and water, or rendering them unavailable for plant uptake, is one of the challenges facing soil and plant scientists. Adequate micronutrient supply is also a potential tool for helping to manage plant diseases, to which results using Mn attest.

In most cases, soil-management practices that avoid extremes in soil pH, that optimize the return of plant residues and animal manures, that encourage mycorrhizae, and that promote chelate production by actively decomposing organic matter and rhizosphere bacteria will minimize the risk of micronutrient deficiencies or toxicities. But increasingly, micronutrient problems need to be at least partially addressed by the application of fertilizers containing these elements in plant available form. Such materials are becoming common components of commercial fertilizers for field and garden use and will likely become even more so in the future.

STUDY QUESTIONS

1. If a forest soil has 5 mg/L (ppm) of Al^{3+} ions and 5 mg/L of Ca^{2+} ions in the soil solution, what is the *molar* ratio of Ca/Al in that solution? (That is, the ratio of mol_c Ca^{2+}/mol_c Al^{3+}, as presented in Table 15.4.)
2. Which is likely to be a better indicator of acidification stress on forest trees, a molar ratio of Ca/Al in leaf tissue less than 1.0 or a molar ratio of Ca/Mn less than 1.0 in the leaf tissue? Why?
3. What portion of the plant would you look at to find symptoms of Ca and Mg deficiencies, respectively?
4. During a year's time, some 250 kg nitrogen and only 30 g molybdenum have been taken up by the trees growing on a hectare of land. Would you therefore conclude that the nitrogen was more essential for the tree growth? Explain.
5. What are phytoliths and what roles do they play in plants and soils?
6. In soils that are inherently low in soluble silica, what three types of benefits you might expect plants to derive from applications of such soil amendment as Wollastinite?
7. Even though only small quantities of micronutrients are needed annually for normal plant growth, would it be wise to add large quantities of these elements now to satisfy future plant needs? Explain.
8. Iron deficiency is common for peaches and other fruits grown on highly alkaline irrigated soils of arid regions, even though these soils are quite high in iron. How do you account for this situation, and what would you do to alleviate the difficulty?
9. How do Fe and Al oxides affect the availability of Mo and B in soils? Explain.
10. Give two examples of fungal-caused plant diseases that can be effectively reduced by fertilizing with a micronutrient. Name the micronutrient and explain why it helps control the disease.
11. Soybeans growing on a recently limed soil show evidence of a deficiency of a nutrient, thought by some to be molybdenum. Do you agree with this diagnosis? If not, what is your explanation?
12. What are *chelates*, how do they function, and what are their sources?
13. The addition of only 1 kg/ha of a nutrient to an acid soil on which lime-loving cauliflower was being grown gave considerable growth response. Which of the nutrients would it likely have been? Explain.
14. Two Aridisols, both at pH 8, were developed from the same parent material, one having restricted drainage, the other being well drained. Plants growing on the well-drained soils showed iron deficiency symptoms while those on the less-well-drained soil did not. What is the likely explanation for this?
15. Animals, both domestic and wild, are adversely affected by deficiencies and toxicities of two of the micronutrients. Which elements are these, and what are the conditions responsible for their effects?
16. Discuss the role plant breeders and geneticists might play in managing micronutrient deficiencies and toxicities.
17. Since boron is required for the production of good-quality table beets, some companies purchase only beets that have been fertilized with specified amounts of this element. Unfortunately, an oat crop following the beets does very poorly compared to oats following unfertilized beets. Give possible explanations for this situation.

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REFERENCES

Agbenin, J. O., and L. A. Olojo. 2004. "Competitive adsorption of copper and zinc by a Bt horizon of a savanna Alfisol as affected by pH and selective removal of hydrous oxides and organic matter." *Geoderma* **119**:85–95.

Alloway, B. J., and R. D. Graham. 2008. "Micronutrient deficiencies in crops and their global significance." *Micronutrient Deficiencies in Global Crop Production*. Springer, Amsterdam, pp. 41–61.

Brady, N., and R. Weil 1996. *The Nature and Properties of Soils*. 11th ed. Prentice Hall, Upper Saddle River, NJ.

Baligar, V. C., N. K. Fageria, and M. A. Elrashidi. 1998. "Toxicity and nutrient constraints to root growth." *Hortscience* **33**:960–965.

Clemens, D. F., B. M. Whitehurst, and G. B. Whitehurst. 1990. "Chelates in agriculture." *Fertilizer Research* **25**:127–131.

Cooke, J., and M. R. Leishman. 2011. "Is plant ecology more siliceous than we realise?" *Trends in Plant Science* **16**:61–68.

Fageria, N. K. 2009. *The Use of Nutrients in Crop Plants*. CRC, Boca Raton FL, USA Press.

Fageria, N. K., V. C. Baligar, and R. B. Clark. 2002. "Micronutrients in crop production." *Advances in Agronomy* **77**:185–268.

Fan, M.-S., F.-J. Zhao, S. J. Fairweather-Tait, P. R. Poulton, S. J. Dunham, and S. P. McGrath. 2008. "Evidence of decreasing mineral density in wheat grain over the last 160 years." *Journal of Trace Elements in Medicine and Biology* **22**:315–324.

Farnham, M. W., and M. A. Grusak. 2014. "Assessing nutritional changes in a vegetable over time: Issues and considerations." *HortScience* **49**:128–132.

Fenn, M. E., T. G. Huntington, S. B. Mclaughlin, C. Eagar, and R. B. Cook. 2006. "Status of soil acidification in North America." *Journal of Forest Science* **52**:3–13.

Francis, D. 1982. *Banker*. Penguin, London, p. 320.

Frankenberger, W. T., and M. E. Losi. 1995. "Applications of bioremediation in the cleanup of heavy metals and metalloids." SSSA Special Publication 43. Soil Science Society of America, Madison, WI.

Gao, X., C. Zou, X. Fan, F. Zhang, and E. Hoffland. 2006. "From flooded to aerobic conditions in rice cultivation: Consequences for zinc uptake." *Plant Soil* **280**:41–47.

Garvin, D. F., R. M. Welch, and J. W. Finley. 2006. "Historical shifts in the seed mineral micronutrient concentration of U.S. hard red winter wheat germplasm." *Journal of the Science of Food and Agriculture* **86**: 2213–2220.

Goldberg, S., H. S. Forster, and C. L. Godfrey. 1996. "Molybdenum adsorption on oxides, clay minerals, and soils." *Soil Science Society of America Journal* **60**:425–432.

Guntzer, F., C. Keller, and J.-D. Meunier. 2012. "Benefits of plant silicon for crops: A review." *Agronomy for Sustainable Development* **32**:201–213.

Hamilton, M. A., D. T. Westermann, and D. W. James. 1993. "Factors affecting zinc uptake in cropping systems." *Soil Science Society of America Journal* **57**:1310–1315.

Hayes, K. F., and S. J. Traina. 1998. "Metal ion speciation and its significance in ecosystem health." In P. M. Huang, D. C. Adriano, T. J. Logan, and R. T. Checkai (eds.). *Soil Chemistry and Ecosystem Health.* SSSA Special Publication 52. Soil Science Society of America, Madison, WI.

Haynes, R. J., O. N. Belyaeva, and G. Kingston. 2013. "Evaluation of industrial wastes as sources of fertilizer silicon using chemical extractions and plant uptake." *Journal of Plant Nutrition and Soil Science* **176**:238–248.

Heckman, J. R., B. B. Clarke, and J. A. Murphy. 2003. "Optimizing manganese fertilization for the suppression of take-all patch disease on creeping bentgrass." *Crop Science* **43**:1395–1398.

Hossain, M. F. 2006. "Arsenic contamination in Bangladesh—An overview." *Agriculture, Ecosystems & Environment* **113**:1–16.

Jin, C., Y. Q. Ye, and S. J. Zheng. 2014. "An underground tale: Contribution of microbial activity to plant iron acquisition via ecological processes." *Annals of Botany* **113**:7–18.

Johnson, A. H., A. Moyer, J. E. Bedison, S. L. Richter, and S. A. Willig. 2008. "Seven decades of calcium depletion in organic horizons of Adirondack forest soils." *Soil Science Society of America Journal* **72**:1824–1830.

Kalim, S., Y. P. Luthra, and S. K. Gandhi. 2003. "Cowpea root rot severity and metabolic changes in relation to manganese application." *Journal of Phytopathology* **151**:92–97.

Kogelmann, W. J., and W. E. Sharpe. 2006. "Soil acidity and manganese in declining and nondeclining sugar maple stands in Pennsylvania." *Journal of Environmental Quality* **35**:433–441.

Kopittke, P. M., and N. W. Menzies. 2007. "A review of the use of the basic cation saturation ratio and the "ideal" soil." *Soil Science Society of America Journal* **71**:259–265.

Lawrence, G., and T. G. Huntington. 1999. "Soil-calcium depletion linked to acid rain and forest growth in the eastern United States." *Science for a Changing World Report*, WRIR 98-4267. U.S. Geological Survey. bqs.usgs.gov/acidrain/WRIR984267.pdf.

Lindsay, W. L. 1972. "Inorganic phase equilibria of micronutrients in soils." In J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay (eds.). *Micronutrients in Agriculture*. Soil Science Society of America, Madison, WI.

Lovley, D. R. 1996. "Microbial reduction of iron, manganese and other metals." *Advances in Agronomy* **54**:175–231.

Lucas, Y., F. Luizao, A. Chauvel, J. Rouiller, and D. Nahon. 1993. "The relation between biological activity of the rain forest and mineral composition of soils." *Science* **260**:521–523.

FOR REFERENCE PURPOSES ONLY

Marschner, H., A. Kalisch, and V. Romheld. 1974. "Mechanism of iron uptake in different plant species." *Proceedings of the 7th International Colloquium on Plant Analysis and Fertilizer Problems*, Hanover, West Germany.

Mengel, K., and J. M. Kirby. 2001. *Principles of Plant Nutrition*. Kluwer Academic Publishers, Dordrecht, Netherlands, p. 864.

Murphy, L. S., and L. M. Walsh. 1972. "Correction of micronutrient deficiencies with fertilizers." In J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay (eds.). *Micronutrients in Agriculture*. Soil Science Society of America, Madison, WI.

Myneni, S. C. B., T. K. Tokunaga, and G. E. Brown. 1997. "Abiotic selenium redox transformations in the presence of Fe (II,III) oxides." *Science* **278**:1106–1109.

Naidu, R., E. Smith, G. Owens, P. Bhattacharya, and P. Nadebaum (eds.). 2006. *Managing Arsenic in the Environment: From Soil to Human Health*. CSIRO Publishing, Collingwood, Australia, p. 656.

Rashid, A., and J. Ryan. 2004. "Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: A review." *Journal of Plant Nutrition* **27**:959–975.

Richards, B. K., T. Steenhuis, J. Peverly, and M. B. McBride. 1998. "Metal mobility at an old heavily loaded sludge application site." *Environmental Pollution* **99**:365–377.

Sarkar, D., D. K. De, R. Das, and B. Mandal. 2014. "Removal of organic matter and oxides of iron and manganese from soil influences boron adsorption in soil." *Geoderma* **214–215**:213–216.

Sillanpaa, M. 1982. *Micronutrients and the Nutrient Status of Soils: A Global Study*. U.N. Food and Agricultural Organization, Rome.

Sommer, M., D. Kaczorek, Y. Kuzyakov, and J. Breuer. 2006. "Silicon pools and fluxes in soils and landscapes—a review." *Journal of Plant Nutrition and Soil Science* **169**:310–329.

Stein, A. 2010. "Global impacts of human mineral malnutrition." *Plant and Soil* **335**:133–154.

Tavakkoli, E., G. Lyons, P. English, and C. N. Guppy. 2011. "Silicon nutrition of rice is affected by soil pH, weathering and silicon fertilisation." *Journal of Plant Nutrition and Soil Science* **174**:437–446.

Taylor, M. Z. 2005. "No bad soils." AgWeb.com division of Farm Journal, Inc. http://www.agweb.com/get_article.asp?sigcat=topproducer&pageid=117257 (posted 26 August 2005; verified 26 August 2006).

The World Bank. 2013. *The Global Burden of Disease: Generating Evidence, Guiding Policy— Sub-Saharan Africa Regional Edition*. Institute for Health Metrics and Evaluation and Human Development Network, Seattle, WA. www.healthmetricsandevaluation.org

Vieira, R. F., E. J. B. N. Cardoso, C. Vieira, and S. T. A. Cassini. 1998. "Foliar application of molybdenum in common beans: I. Nitrogenase and reductase activities in a soil of high fertility." *Journal of Plant Nutrition* **21**:169–180.

Viets, F. J., Jr. 1965. "The plants' need for and use of nitrogen." *Soil Nitrogen*, Agronomy No. 10. American Society of Agronomy, Madison, WI.

Weil, R. R., C. D. Foy, and C. A. Coradetti. 1997. "Influence of soil moisture regimes on subsequent soil manganese availability and toxicity in two cotton genotypes." *Agronomy Journal* **89**:1–8.

Weil, R. R., and S. S. Holah. 1989. "Effects of submergence on the availability of micronutrients in three Ultisols." *Plant and Soil* **114**:147–157.

Welch, R. M. 1995. "Micronutrient nutrition of plants." *Critical Reviews in Plant Science* **14**(1):49–82.

Wood, B. W., C. C. Reilly, and A. P. Nyczepir. 2004. "Mouse-ear of pecan: A nickel deficiency." *HortScience* **39**:1238–1242.

Wurzburger, N., J. P. Bellenger, A. M. L. Kraepiel, and L. O. Hedin. 2012. "Molybdenum and phosphorus interact to constrain asymbiotic nitrogen fixation in tropical forests." *PLoS ONE* **7**:e33710.

Zayed A. E., E. Pilon-Smits, M. de Souza, Z. Q. Lin, and N. Terry. 2000. "Remediation of selenium-polluted soils and waters by phytovolatilization." In N. Terry and G. Bañuelos (eds.). *Phytoremediation of Contaminated Soil and Water*. Lewis Publishers, New York, pp. 61–83, Chap. 4.

Zuo, Y., and F. Zhang. 2011. "Soil and crop management strategies to prevent iron deficiency in crops." *Plant and Soil* **339**:83–95.

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Cattle not fenced out pollute a stream with nutrients. (Ray R. Weil)

16 Practical Nutrient Management

For every atom lost to the sea, the prairie pulls another out of the decaying rocks. The only certain truth is that its creatures must suck hard, live fast, and die often, lest its losses exceed its gains.
—ALDO LEOPOLD,
A SAND COUNTY ALMANAC *(1949)*

To be good stewards of the land, soil managers must keep nutrients cycling effectively and maintain the soil's capacity to supply the nutritional needs of plants. In both undisturbed natural ecosystems and managed agroecosystems, the supply of nutrients from the soil may limit vegetative productivity to levels below what available supplies of water and solar energy could be expected to support. Interventions to manage nutrients are typically needed for forests, farms, fairways, and flower gardens to efficiently provide us with lumber, food, biofuels, recreational opportunities, and aesthetic satisfaction.

In managed ecosystems, nutrient cycles can become unbalanced through increased removals (e.g., harvest of timber and crops), through increased system leakage (e.g., leaching and runoff), through simplification (e.g., monoculture, be it of corn, pine trees, or sugarcane), through increased demands for rapid plant growth (whether the soil is naturally fertile or not), and through increased animal density (especially if imported feed brings in nutrients from outside the ecosystem). Some of the greatest impacts of land management are felt not on the land but in the water, where excess nutrients play havoc with aquatic ecosystems. Therefore anyone attempting to manage land must also be prepared to take responsibility for nutrient and environmental management as well.

In this chapter we will discuss methods of balancing and enhancing nutrient cycles, as well as sources of additional nutrients that can be applied to soils or plants. We will learn how to diagnose nutritional disorders of plants and correct soil fertility problems. Building on the principles set out in early chapters, this chapter contains practical information on profitable production of abundant, high-quality plants while maintaining the health of both the soil and the rest of the environment.

16.1 GOALS OF NUTRIENT MANAGEMENT[1]

Nutrient management is one aspect of a holistic approach to managing soils in the larger environment. It aims to achieve four broad, interrelated goals: (1) cost-effective production of high-quality plants and animals, (2) maintenance or enhancement of soil health, (3) efficient use and conservation of nutrient resources, and (4) protection of the environment beyond the soil.

[1]For an overview of issues and advances in nutrient management for agriculture and environmental quality, see Magdoff et al. (1997). For estimates of nutrient limitations on global vegetative productivity, see Fisher et al. (2012). For a standard textbook on management of agricultural soil fertility and fertilizers, see Havlin et al. (2014).

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Plant Production

Three of the primary types of plant production in which people engage are: (1) *agriculture*, (2) *forestry*, and (3) *ornamental landscaping.* Agriculturists range from small-scale subsistence farm families or home gardeners who produce mainly for their own use to larger-scale commercial farmers and ranchers whose primary goal is to make a profit by selling the plants and animals they produce. Regardless of the scale, the main nutrient-management goal for agriculture is to increase plant yield and quality thereby helping subsistence-level farmers to feed their families and commercial farmers to enhance their incomes. Unfortunately, farmers in both groups usually judge the success or failure of their management schemes within the period of one or two crop growing seasons, rather than the span of several decades or even human generations that would allow full evaluation of the practices they choose to use.

In forestry, the principal plant product may be measured in terms of volume of lumber or paper produced. In these instances, nutrient management aims to enhance the survival rate of tree seedlings and rate of tree growth so that the time between investment and payoff can be minimized. Wildlife habitat and recreational values may also be primary or secondary products. The time frame in forestry is measured in decades or even centuries, and so tends to limit the intensity of nutrient management interventions that can be profitably undertaken.

When soils are used for ornamental landscaping purposes, the principal objective is to produce quality, aesthetically pleasing plants and land surfaces. Whether the plants are produced for sale or not, relatively little attention is paid to yield of biomass produced. Hardiness, resistance to pests, color, and abundance of blooms are much more important. Labor costs and convenience are generally of more concern than fertilizer costs; hence, expensive, specialty fertilizers are widely used.

Soil Health and Productivity

The concept of using nutrient management to enhance soil health goes far beyond simply supplying nutrients for the current year's plant growth. Rather, it includes the long-term nutrient-supplying and nutrient-cycling capacity of the soil, improvement of soil physical properties or tilth, maintenance of above- and belowground biological functions and diversity, and the avoidance of chemical toxicities. Likewise, the management tools employed go far beyond the application of various fertilizers (although this may be an important component of nutrient management). Nutrient management requires the integrated management of the physical, chemical, and biological processes that comprise soil health (see chapter 20). The impact of fire on soil nutrient and water supplies (Chapter 7), the increase in nutrient availability (and sometimes losses) brought about by earthworm activity (Chapter 11), the effects of tillage on organic matter mineralization (Chapter 12), the contribution of rhizobia–legume symbiosis to nitrogen supplies (Chapter 13), and role of mycorrhizal fungi in phosphorus uptake by plants (Chapter 14), are all examples of soil processes that need to be considered in nutrient management.

Conservation of Nutrient Resources

Two concepts that are key to the goal of conserving nutrient resources are: (1) renewal or reuse of the resources, and (2) nutrient budgeting that reflects a balance between system inputs and outputs.

The first law of thermodynamics suggests that all material resources are ultimately renewable, since the elements are not destroyed by use but are merely recombined and moved about in space. In practical terms, however, once a nutrient has been removed from a plot of land and dispersed into the larger environment, it may be difficult if not impossible to use it again for plant growth. For instance, phosphorus deposited in a lake bottom with eroded sediment and nitrogen buried in a landfill as a component of garbage will not likely be available for reuse. In contrast, soil application of livestock manure or composted municipal garbage and irrigation with treated sewage effluent are practical examples of nutrient reuse.

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Recycling is a form of reuse in which nutrients are returned to the same land from which they were previously removed. Litter fall from perennial vegetation recycles nutrients to the soil naturally. Leaving crop residues in the field and spreading manure onto the land from which the cattle feed was harvested are both examples of managed nutrient recycling. The term *renewable resource* best applies to soil nitrogen, which can be replenished from the atmosphere by biological nitrogen fixation (see Sections 13.10–13.12). Manufacture of nitrogen fertilizers also fixes atmospheric nitrogen, but generally at a large cost in nonrenewable fossil fuel energy.

Other fertilizer nutrients, such as potassium and phosphorus, are mined or extracted from nonrenewable mineral deposits. The size of known global reserves varies according to the nutrient. As farmers, especially in Asia increase their use of phosphorus fertilizer, the world's most high-quality sources of this crucial and irreplaceable element are likely to be depleted within as little as a single century (see Box 14.3). As the best, most concentrated, and most accessible sources of these nutrients are depleted, the cost of producing fertilizer will likely rise in terms of money, energy, and environmental disruption. Therefore, careful husbandry of phosphorus and other nutrient resources must be an integral part of any long-term nutrient management program.

Nutrient Budgets and Balances[2]

Examples of simplified nutrient budgets are shown in Figure 16.1. Addressing nutrient imbalances, shortages, and surpluses may call for analysis of nutrient flows, not just on a single farm or enterprise, but on a watershed, regional, or even national or global scale. For example, many countries in Africa are net exporters of nutrients. That is, river flows and the exports of agricultural and forest products carry with them more nutrients than are imported into the country as fertilizers, food, animal feed, or atmospheric deposition. This net *negative* nutrient balance appears to be a contributing factor in the impoverishment of African soils, leading to low agricultural productivity and rural poverty which in turn serve as a drag on the growth of national economies (see Section 20.10).

By contrast, in most temperate regions, the cultivated land on average receives nutrients in excess of those removed in crops and animal products. In recent years, the nearly 300

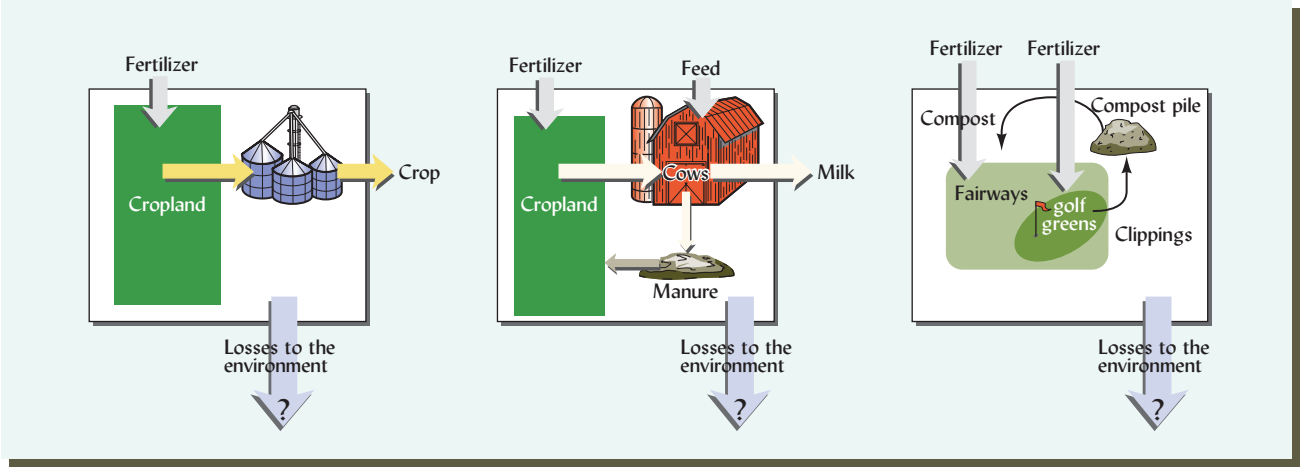

Figure 16.1 *Representative conceptual nutrient flowcharts for a cash-grain farm, a dairy farm, and a golf course. Only the managed inputs, key recycling flows, and outputs are shown. Unmanaged inputs, such as nutrient deposition in rainfall, are not shown. Outputs that are difficult to manage, such as leaching and runoff losses to the environment, are shown as being variable. Although information on unmanaged inputs and outputs is not always readily available, it must be taken into consideration in developing a complete nutrient management plan. Such flowcharts are a starting point in identifying imbalances between inputs and outputs that could lead to wasted resources, reduced profitability, and environmental damage.* (Diagram courtesy of Ray R. Weil)

[2]For an exploration of how global nitrogen and phosphorus budgets have changed due to changes in livestock production, see Bouwman et al. (2013); for a discussion of negative nutrient balance in African soils, see Smaling et al. (1997).

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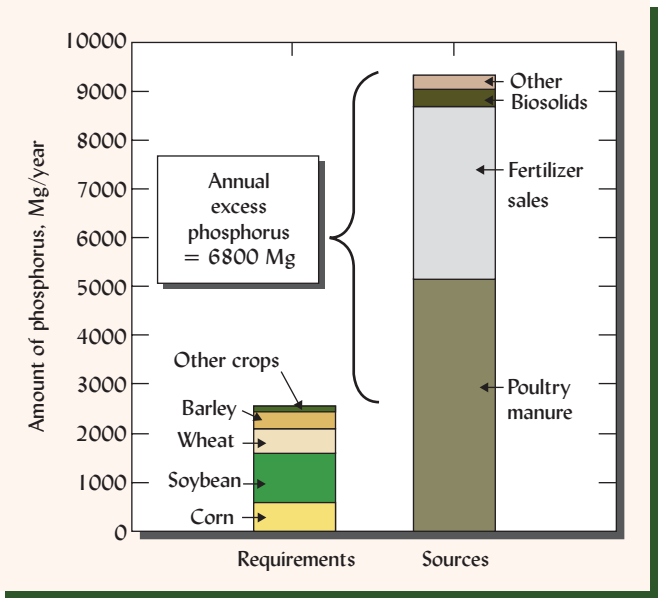

Figure 16.2 *Phosphorus imbalance for the State of Delaware, USA. Crop requirements estimated from recommended fertilizer rates based on soil tests and expected crop responses (see Section 16.11) totaled about 2600 Mg P. The manure generated by the state's poultry industry alone contained about twice as much P as required by all the crops in the state. The total amount of P applied in fertilizers and manures (plus some other P-containing wastes) totaled more than 9400 Mg P, leaving a surplus of more than 6800 Mg P. If the total P sources were spread on all 217,900 ha of cropland in the state, there would be 31 kg/ha of excess P each year. Most of this excess P came from poultry feed imported from other states, and has resulted in P buildup in soils and increased P losses in runoff.* [Graphed from data in Beegle et al. (2002)]

million ha of cultivated temperate-region soils had a net *positive* nutrient balance of at least 60 kg/ha N, 20 kg/ha P, and 30 kg/ha K. While nutrient deficiencies still occur in some locations, the great majority of commercially farmed soils have experienced a nutrient buildup. Some of the excess nutrients move into groundwater, surface waters, or the atmosphere, where they can contribute to environmental damage (Sections 16.2, 14.2, and 13.4).

Changes in the structure of agricultural production, especially the separation of livestock production from crop production, have led to *regional* nutrient imbalances and concomitant serious water-pollution problems. The concentration of livestock production facilities in regions that must import feed from other areas is a case in point. The animal manure produced in these areas contains nutrients far in excess of the amounts that can be used in an efficient and environmentally safe manner by crops in nearby fields. The concentrated poultry industry in Delaware, USA, is one of the first examples for which the imbalance between phosphorus sources and utilization potential was documented (Figure 16.2).

Although many nutrient imbalances and resulting environmental impacts involve localized excessive concentration of nutrients, there are also global imbalances between the total amount of nutrient inputs and outputs, leading to nutrient surpluses that, in the cases of N and P, result in considerable environmental damages. The problem greatly worsened during the second half of the 20th century (Figure 16.3) with development of industrial agriculture based on inorganic fertilizers and concentrated livestock feeding, and is likely to get worse still with the spread of these practices in emerging economies around the world. In the case

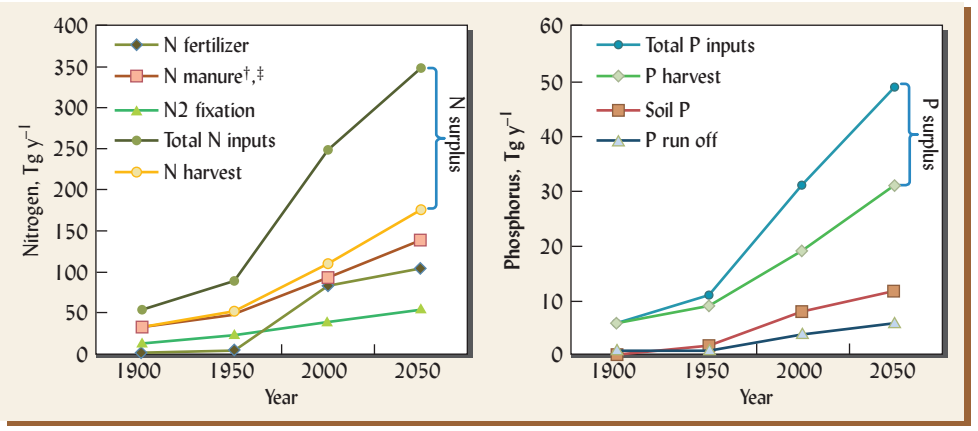

Figure 16.3 *Past and projected agriculture inputs and outputs of nitrogen and phosphorus. The surplus of N or P is the total for all inputs minus harvest (intentional removals such as crops and animal products). Projections for 2050 assume "business as usual." If better nutrient management is widely adapted, future surpluses could be smaller than shown. (Right) Total P input includes both mineral and manure forms. Surplus P goes to accumulation in soils and runoff losses. (Left) Individual N inputs are shown, but for a breakdown of N surplus, see Figure 16.4. Note that the magnitudes for N fluxes are almost ten times greater than for P. Compare to N trends in Figure 13.18.* [Graphed from data in Bouwman et al. (2013)]

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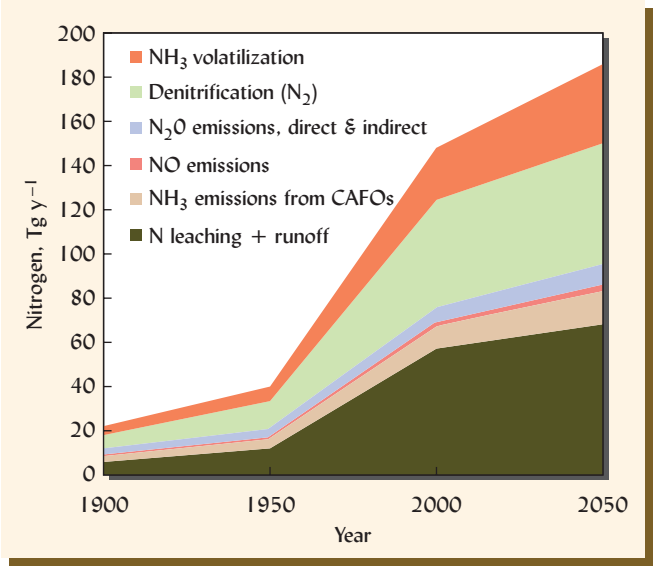

Figure 16.4 *Fates of the global agricultural nitrogen surplus. Except for denitrification to N_2, the output of surplus N via the pathways indicated causes such environmental damages as eutrophication, climate change, and water contamination. See Chapter 13 for details of these nitrogen loss pathways.* [Graphed from data in Bouwman et al. (2013)]

of phosphorus (Figure 16.3, *right*), about two-thirds of the growing surplus is expected to accumulate in agricultural soils (see Section 14.9), while about one-third will run off the land into aquatic systems. In the case of nitrogen, the fate of the surplus is more complex. About one-third of the surplus N is denitrified to N_2 gas which returns to the atmosphere with no adverse effects. However the rest of the N surplus is either transformed into greenhouse gases that accelerate climate change or to nitrate and ammonia that can end up causing eutrophication and toxicity in aquatic and forest systems (see Figure 16.4 and Sections 13.13–13.15).

16.2 NUTRIENTS AS POLLUTANTS

Nutrient management impacts the environment most directly with water-quality problems caused by N and P. Together, these two nutrients are the most widespread cause of water-quality impairment in lakes and estuaries, and are second only to sediment (see Section 17.2) among pollutants impairing the water quality of rivers and streams.

Nutrient Damage to Aquatic Ecosystems

As explained in Chapters 13 and 14 (Boxes 13.3 and 14.1), the growth of aquatic plants (e.g., algae and phytoplankton) often explodes when concentrations of N or P exceed critical levels, leading to numerous undesirable effects in the aquatic ecosystem, including low oxygen and blooms of toxic algal. In most freshwater lakes and streams, P is the limiting nutrient that can set off eutrophication; as little as 0.02 mg/L of total P is thought to be potentially damaging. In saltier waters (estuaries and ocean coastal areas), N is usually the nutrient most likely to cause eutrophication (see Box 13.3). Levels of total dissolved N above 2 mg/L are often considered above normal and damaging to the ecosystem. In addition to stimulating eutrophication, N in the form of dissolved ammonia gas (NH_3) can be directly toxic to fish. For this reason, average levels of ammonium-N (which is in equilibrium with ammonia) should be kept below 2 mg/L. The nitrate form of N is also of concern, as levels above 10 mg nitrate-N/L are considered unfit for human drinking water (see Box 13.2).

Most industrialized countries have made great strides in reducing nutrient pollution from factory and municipal sewage outfalls (called **point sources** because these sources are clearly localized). Figure 14.6 illustrates success in reducing point source P pollution to Lake Erie, on the border between the USA and Canada during the 1970–1980s. However, much less progress has been made in controlling nutrients in the water coming from landscapes (called **nonpoint sources** because these sources are diffuse and not easily identified). The nature of the landscape generally dictates the impact on water quality. Streams draining forestland and rangeland are generally far lower in nutrients than those draining watersheds

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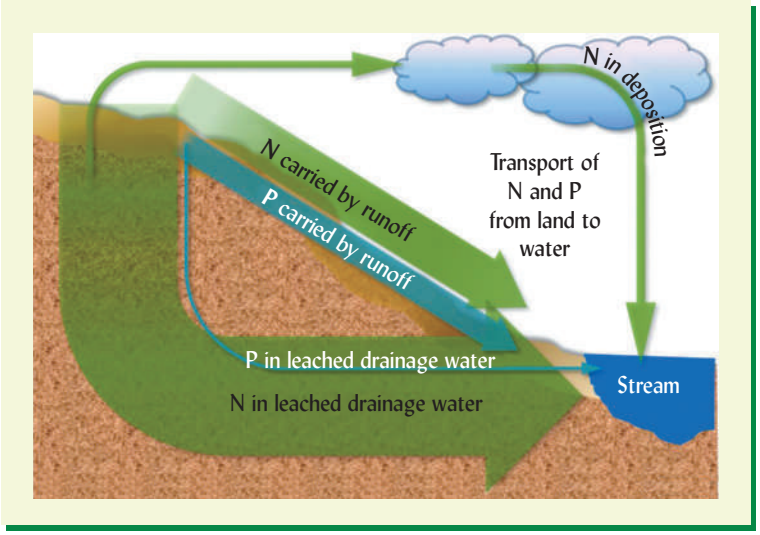

Figure 16.5 *Nitrogen moves from land to streams mainly dissolved in drainage water, while phosphorus is carried mainly in surface runoff. Therefore control of P loading usually focuses on reduced runoff and erosion, while control of N loading usually focuses on reduced leaching. Some nitrogen leaves the soil in gaseous forms that may be deposited in water from the atmosphere.* (Diagram courtesy of Ray R. Weil)

dominated by agricultural and urban land uses. Two examples are worth considering, as follows. Scientists estimate that agricultural activities account for some 40% of the N and P loads to the Chesapeake Bay from its 170,000 km^2 watershed (on the U.S. Atlantic Coast), while point sources (sewage and industrial plants) and urban runoff (including septic systems) each account for another 20%. In the more intensively farmed and less densely populated Mississippi River basin covering nearly 3 million km^2, some 70% of the N and 80% of the P load come from agriculture and only 6% from point sources and 10% from urban runoff.

Since agricultural land is the major source of non-point nutrient pollution in most watersheds, it is important to consider the pathways by which these two offending nutrients find their way to the waters they pollute. Although soils and watersheds differ, we can make some general statements about N and P transport from land to water (Figure 16.5). Most commonly the rate of loss or loading to streams is about an order of magnitude greater for N than for P. Also the main pathways differ for the two nutrients. Nitrogen makes its way to streams mainly by the leaching of dissolved forms (nitrate, ammonium, and dissolved organic N) to shallow ground water and then by subsurface flow to the streams. Phosphorus, on the other hand, tends to move off the land primarily in surface runoff, either as part of mineral or organic particles, or as dissolved inorganic and organic compounds in the runoff water. Except in certain low-lying, artificially drained soils, very little P moves by subsurface flow because of the strong attraction between mineral soil particles and dissolved inorganic P (see Section 14.5). The data in Table 16.1 describing the average N and P loading per unit land

Table 16.1
AVERAGE ANNUAL LOSSES OF NUTRIENTS AND SEDIMENT BY SURFACE RUNOFF AND LEACHING FROM CROPLAND IN THE CHESAPEAKE BAY WATERSHED IN THE UNITED STATES
Values are estimates of losses at the edge of an average crop field. Nitrogen is lost predominately by leaching and phosphorus predominately in surface runoff. Compare to Figure 16.5.

	Surface runoff	Subsurface (leaching)	Total loss
		kg/ha	
Nitrogen loss	9.98	36.7	46.6
Phosphorus loss	4.11	0.08	4.19
Sediment loss	1320	0	1320

Data selected from USDA economic research service estimates (Ribaudo et al., 2014).

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Table 16.2
TYPICAL COMPONENTS OF A NUTRIENT MANAGEMENT PLAN
This chapter explains many of the tools used to plan for nutrient application to land in a manner that maximizes nutrient-use efficiency and minimizes water pollution risks.

- Aerial photo, map and soil map of site
- Current and/or planned plant production sequences or crop rotations
- Soil test results and recommended nutrient application rates
- Plant tissue analysis results
- Nutrient analysis of manure or other soil amendments
- Realistic yield goals and a description of how they were determined
- A complete nutrient budget for N, P, and K in the production system
- An accounting of all nutrient inputs such as fertilizers, animal manure, sewage sludge, irrigation water, compost, and atmospheric deposition
- Planned rates, methods, and timing of nutrient applications
- Location of environmentally sensitive areas or resources, if present
- The potential risk of N and/or P water pollution as assessed by a *N leaching index*, a *P site index*, or other acceptable assessment tools

area in the Chesapeake Bay watershed is typical of many humid region watersheds and confirms the trends just described. An understanding of the different pathways traveled by N and P is essential in designing management practices aimed at reducing nutrient pollution.

Nutrient Management Plan

One tool for reducing nonpoint source N and P pollution is a nutrient management plan—a document that records an integrated strategy and specific practices for how nutrients will be used in plant production (Table 16.2). Increasingly, these plans are seen as legal documents and may be required by government program aimed at reducing nonpoint source nutrient pollution. Generally, the document is prepared by a specially trained soil scientist who consults closely with the landowner to meet both environmental goals and the practical needs. The plan attempts to balance the inputs of N and P (and other nutrients) with their desirable outputs (i.e., removal in harvested products) to prevent undesirable outputs (runoff, leaching) that exceed allowable **total maximum daily load** (TMDL), the largest amount of nutrient runoff and leaching (measured as g ha^{-1} day^{-1}) permitted from an area of land. An important component of many nutrient management plans, the *P site index*, is explained in Section 16.12.

Best Management Practices (BMPs)

The primary means of preventing nutrient pollution of waters is to avoid excessive applications of N and P onto the landscape to begin with. One of the reasons nutrient balance and avoidance of surpluses on agricultural land are so important is that a large proportion of the surplus usually makes its way to water. Figure 16.6 illustrates this point. In well-drained cropland some 80% of surplus N leaches below the crop root zone. Perennial grasslands tend not to exhibit as much N leaching until the N surplus becomes quite large.

In addition to avoiding additional nutrient surpluses, it is important to manage soils and plants to reduce the transport of nutrients (and other pollutants) from soils to groundwater and surface waters. In the United States, practices officially sanctioned to implement nutrient input and transport reduction strategies are known as BMPs. Several BMPs designed to avoid additional surpluses will be discussed later in this chapter. Here we will focus on four general types of practices aimed at controlling nutrient transport to water: (1) buffer strips, (2) cover crops, (3) conservation tillage, and (4) forest stand management.

Buffer Strips

Buffer strips of dense vegetation are a simple and generally cost-effective method to protect water from the polluting effects of a nutrient-generating land use. The vegetation in the buffer

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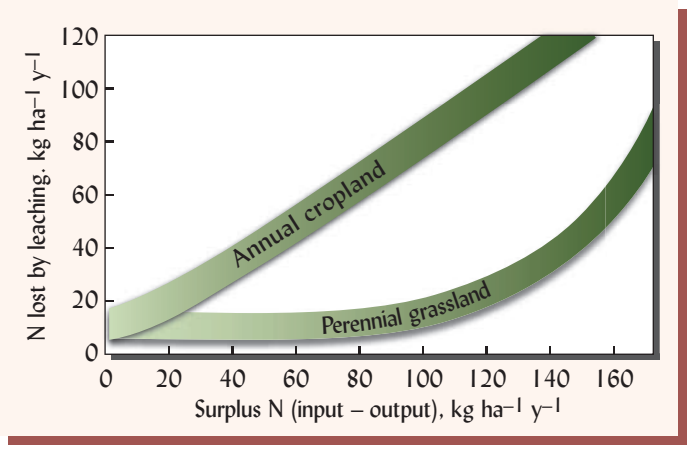

Figure 16.6 *Nitrogen losses by leaching from humid region upland agricultural soils are related to the nitrogen surplus—the amount by which the nitrogen added from all sources exceeds the nitrogen removed in harvested products. While some N may accumulate temporarily in the soil organic matter and some may be lost to the atmosphere by denitrification, typically in well-drained cropland about 80% of the surplus N leaches below the crop root zone. In permanent grassland used for harvesting forage or pasturing livestock, soil storage and denitrification tend to account for most of the surplus N up to a threshold beyond which leaching losses follow a pattern similar to that exhibited by cropland.* [Graph based on concepts in Billen et al. (2013)]

Figure 16.7 *A forest riparian buffer separates the Connecticut River from alluvial farmland in western Massachusetts in the United States.* (Photo courtesy of Ray R. Weil)

strips may consist of existing natural vegetation or planted species, including grasses, shrubs, trees (Figure 16.7), or a combination of these vegetation types (Figure 16.8).

Riparian Buffers. Buffer strips situated along the banks (the **riparian zone**) of a stream or other water body are termed *riparian buffers*. Water running off the surface of nutrient-rich land passes through the riparian buffer before it reaches the stream. Trees (and their litter layer) or grass plants (and their thatch layer) reduce water velocity and increase the tortuosity of the water's travel paths. Under these conditions, most of the sediment and attached nutrients will settle out of the slowly flowing water. In addition, dissolved nutrients are adsorbed by the soil, immobilized by microorganisms, or are taken up by plants growing in the buffer strip. The decreased flow velocity also increases the retention time—allowing a greater length of time during which microbial action can break down pesticides before they reach the stream. Under some circumstances, buffer strips along streams can also reduce the nitrate levels in the groundwater flowing under them (although emission of nitrous oxide to the atmosphere may be a consequence of nitrate reduction; see Figure 13.17).

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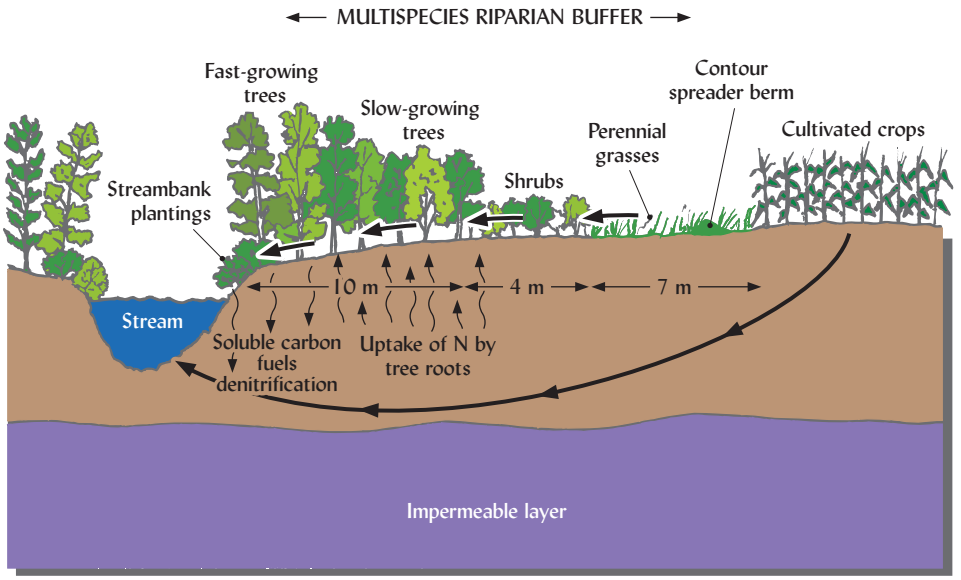

Figure 16.8 *A multispecies riparian buffer strip designed to protect the stream from nutrients and sediment in cropland runoff while also providing wildlife habitat. A grass-covered level berm spreads runoff water evenly to avoid gullies. Perennial grasses filter out sediments and take up dissolved nutrients. Deep tree roots remove nutrients from shallow groundwater. Soluble carbon from tree litter percolates downward to provide energy for anaerobic denitrifying bacteria that remove additional nitrogen from groundwater. Woody vegetation provides wildlife habitat, shade to cool the stream, and woody debris for fish habitat. A total buffer width of 10–20 m can usually provide most of these potential benefits.* (Diagram courtesy Ray R. Weil)

Design and Management of Riparian Buffers. For optimal performance, some land grading may be needed when the buffers are established to ensure that the runoff water is spread out evenly as opposed to flowing through in concentrated in rivulets. To preserve the dense vegetation and litter cover, riparian zones should be kept off limits to timber harvest machinery, and if the adjacent land is grazed, cattle should be fenced out. The width needed for optimum cleanup may vary from 6 to 60 m, although a width of 10–20 m is usually sufficient to obtain most of the nutrient- and sediment-removal benefits on slopes of less than 8% (Figure 16.8). Occasional mowing of the grassy zone or thinning of tree stands may help maintain high rates of nutrient uptake. Setting land aside as a buffer often represents a significant reduction in harvestable cropland or timberland (See Figure 17.31, *left*). However, a well-designed buffer strip can provide real benefits, some of which directly accrue to the landowner: turnaround space for field equipment, valuable hay from grass buffers, improved fishing by shading the stream and providing large woody debris for fish habitat, and enhanced recreational values associated with increased wildlife populations. Thus, installation of riparian buffer strips can often be a win-win situation.

In-Field Contour Buffer Strips. Small buffer areas upslope from the riparian zone, often in the agricultural fields themselves can also be effective in preventing the loss of nutrients in runoff. Various spatial configurations and types of vegetation can be used for this purpose. Nutrient retention can be coupled with biodiversity and wildlife benefits if multiple species of native perennial grasses and forbs are used in the buffer areas. Generally, most of the nutrient and sediment removal takes place in the first 3–6 m of flow through buffer vegetation. If contour buffer strips are used, these can be as narrow as 3 m and occupy less than 10% of the field area, leaving 90% or more of the land to grow crops. However, research suggests that it is just as effective and more convenient for farming operation if the buffer area is consolidated into a single buffer area at the mouth of each small cropland watershed (Figure 16.9).

Cover Crops for Nutrient Management

Instead of being harvested, a *cover crop* is grown to provide vegetative cover for the soil and then is killed and either left on the surface as a mulch, or tilled into the soil as a *green manure.* Cover crops generally occupy a niche in time (early or late off-seasons or other time periods when regular cash crops are not grown) or space (between widely spaced vines or fruit trees or between rows of annual crops) that minimizes competition with regular agriculture crops grown for income. In climates with enough precipitation to allow for some water use by the cover crop, they can help farmers improve soil health and biodiversity (see section 20.4).

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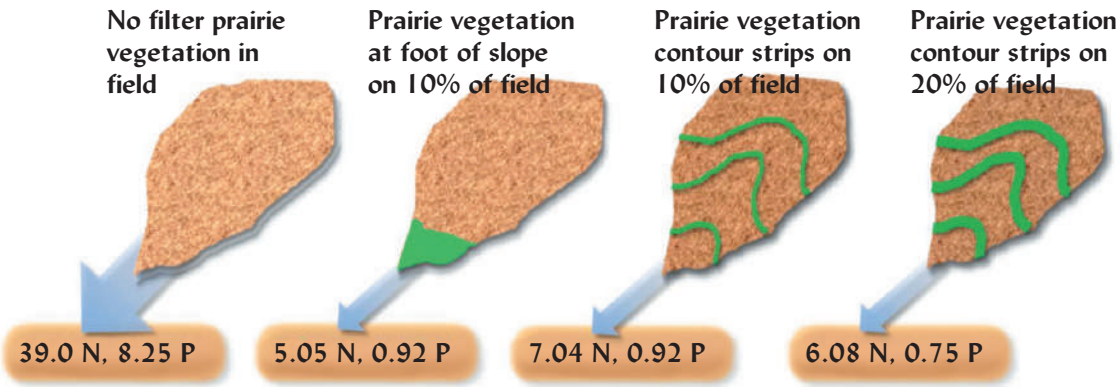

Figure 16.9 *Effectiveness of perennial herbaceous (prairie) vegetation filters for reducing nutrient loss from cropland. A diverse mixture of native prairie forbs and grasses was seeded in portions of a crop field (shown in green), either in 3–6 m wide contour strips or in the bottom of the watershed. The three practices shown all reduced nutrient losses by >80%, but planting prairie vegetation in only the bottom 10% of a field proved to be the most convenient and economical practice to impliment. The soils were Hapludalfs and Argiudolls with 6–10% slopes. A notill soybean–corn rotation was grown with 135–185 kg N ha^{-1} and 50 kg P ha^{-1} applied to the corn crops. Despite initial concerns, the prairie vegetation did not contribute weeds to any of the fields.* [Data and concepts selected from Zhou et al. (2014)]

Other roles for cover crops include protecting the soil from the erosive forces of wind and rain (see Section 17.7); adding to the soil organic matter (see Section 12.7); alleviating soil compaction (see Section 4.7); and, if leguminous, increasing the available nitrogen in the soil (see Section 13.15).

Cover crops can also reduce the loss of nutrients and sediment in surface runoff. First, the protective foliage and litter prevent the formation of a crust at the soil surface, thus maintaining a high rate of infiltration (see Figure 6.9, *right*) and reducing runoff. Second, for the runoff that does occur, the cover crop helps remove both sediment and nutrients by the same mechanisms that operate in a buffer strip, as previously described.

Cover Crops Reduce Leaching Losses. Cover crops can also serve as important nutrient management tools to reduce the leaching losses of nutrients, principally nitrogen (Figure 16.10). In many temperate humid regions, the greatest potential for leaching of nitrogen from cropland occurs when rainfall or snowmelt is high and evapotranspiration by vegetative is low; for example, during the periods of unfrozen soil between crop maturity in early fall and the establishment of a new crop root system in spring. The main crop is not taking up soil N but soluble soil nitrogen continues to be produced by decomposition and leaches downward. During this time of vulnerability, an actively growing cover crop will

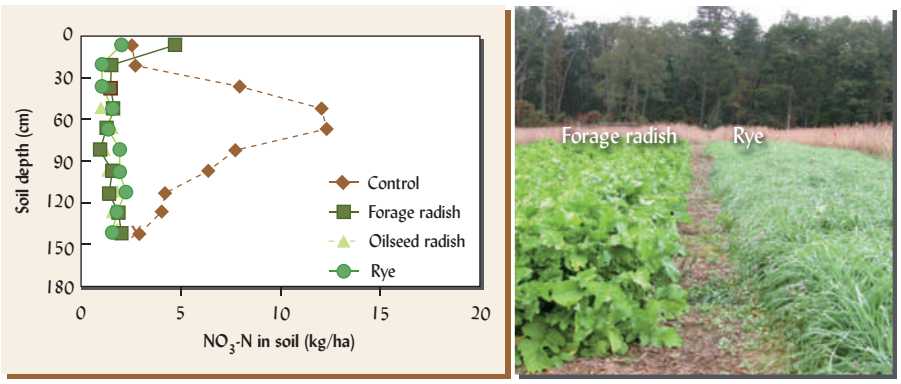

Figure 16.10 *Cover crops can capture soluble nitrogen (e.g., NO_3-N) left in the soil profile after the main cropping season, thus substantially reducing N loss to groundwater during the winter. Forage radish and rye (photo) are cover crops capable of capturing > 100 kg/ha of such residual N in fall, cleaning the soil profile of soluble N to considerable depths. The graph shows nitrate-N in November, expressed as kg N/ha for each 15 cm depth increment of this sandy Ultisol. The control plots had some weeds, but no cover crop.* [Data from Dean and Weil (2009); photo courtesy of Ray R. Weil]

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reduce both the percolation of water and the nitrogen concentration in the water that does percolate, incorporating this nutrient into plant tissues. For this purpose, an ideal cover crop should rapidly produce an extensive and deep root system capable of catching the soluble nitrogen *before* it moves so deep into the soil that it will be subject to leaching away over winter. To accomplish this purpose, the cover crop should be established early enough to capture the soluble soil nitrogen in the fall during the weeks just before and after harvest time and not rely primarily on growth early in the following spring (Figure 16.11). If the cover crop maintains a low C/N ratio and produces easily decomposed residues, the nitrogen so captured will largely be released in time for use by the next spring-planted main crop. To accomplish these goals, farmers are experimenting with methods for earlier planting of cover crops. These include adopting cropping systems that allow earlier harvests with the use of winter cereals in the rotation or more rapidly maturing summer crop varieties. The use of airplanes and special high-clearance machines allow farmers to sow cover crop seeds weeks or even months before the main crop is harvested from a field.

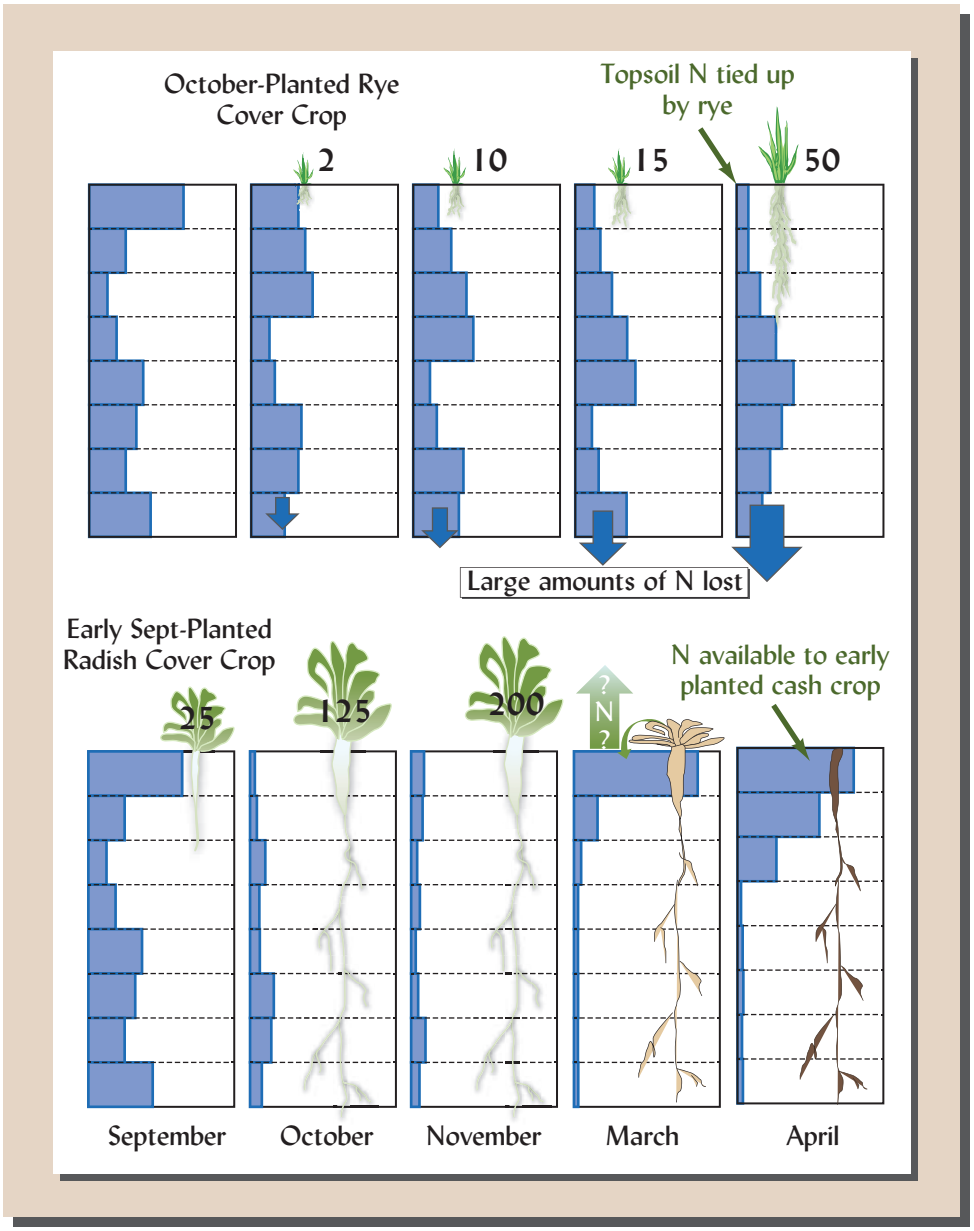

Figure 16.11 *Early sowing of fast-growing, deeply rooting cover crops in temperate humid regions may capture of soluble nitrogen from deep in the soil before it escapes during the main winter leaching season. A cover crop species which is killed by extremely cold temperatures over winter and whose residues then decompose rapidly when the soil warms in the following spring may return much of the captured nitrogen to the topsoil layer where it can be used by an early spring-planted main crop, thus reducing the amount of fertilizer nitrogen needed. The scenarios in the diagram are for a climate in which N uptake by the summer crop is finished by early September, and killing cold occurs after November. The numbers indicate the expected kg/ha of N in the cover crop biomass. The blue bars indicate expected amounts of soluble N in 30 cm increments of the soil profile.* (Diagram courtesy of Ray R. Weil)

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Largely because of their more rapid root growth in fall, winter annual cereals (rye, wheat, oats) and Brassicas (rape, forage radish, turnips, mustards) have proven to be more efficient than legumes (vetch, clover, etc.) at mopping up leftover soluble nitrogen. Some of the most effective cover crops may be complex mixtures of three or more species that perform in complementary ways.

A cover crop, like any plant, requires an adequate nutrient supply. If the surface soil in which the seeds germinate is so poorly supplied with nutrients (including N!) that growth is retarded, subsoil nitrogen is likely to leach deeply before the cover crop roots can become established. On sandy, low organic matter soils it may even be necessary to apply a very small dressing of N in fall to promote vigorous cover crop growth that will enable the roots to catch up with N already moved deeply into the profile.

Conservation Tillage

The term **conservation tillage** applies to agricultural practices that keep at least 30% of the soil surface covered by plant residues. The effects of conservation tillage on soil properties and on the prevention of soil erosion are discussed elsewhere in this textbook (see Sections 4.6, 6.4, and 17.6). Here, we emphasize the effects on nutrient losses.

Compared to plowed fields with little residue cover, conservation tillage usually reduces the total amount of water running off the land surface, whether from rainfall or snowmelt. It reduces even more the load of nutrients and sediment carried by that runoff (Figure 16.12 and Table 14.2). When combined with a cover crop, the reductions are greater still. Except, perhaps, when heavy rain closely follows the spreading of manure or sewage sludge on the land surface (see Section 16.4), the less the soil surface is disturbed by tillage, the smaller are the losses of nutrients in surface runoff. The relatively small amounts of nutrients in runoff from untilled land (no-till cropland, pastures, and forests) tend to be mostly dissolved in the water rather than attached to sediment particles, while the reverse is true for tilled land. Because of large, sediment-associated nutrient losses, the total nutrient loss in surface runoff from sloping conventionally tilled land generally is far greater than that from land where no-till or conservation tillage methods are used.

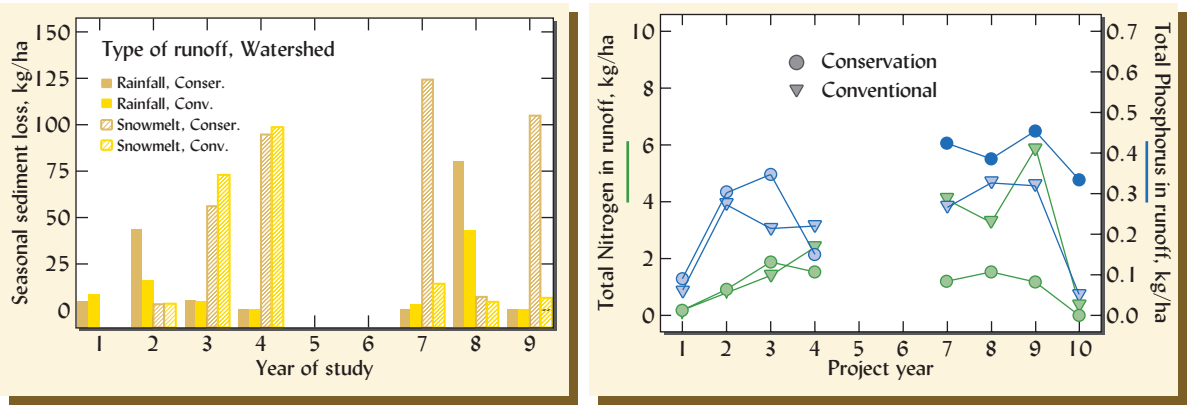

Figure 16.12 *Sediment and nutrients lost in runoff from a pair of watersheds growing a wheat, flax, and canola rotation in Manitoba, Canada. Runoff from snowmelt (light fill) and rainfall (dark fill) are shown. During years 1–4 the watersheds were managed exactly the same to collect baseline data.* (Left) *The data confirm that brown and yellow-coded watersheds lost very similar amounts of sediment in runoff from snowmelt and rainfall (except for a small difference in year 2). Between years 4 and 7, the watershed coded yellow was converted to conservation tillage (which left 50–60% of the surface covered with plant residues), while the watershed coded brown was managed with conventional full tillage (which left less than 20% of the surface covered with residues). During the four years after the conversion, the conservation tillage watershed lost much less sediment than did the watershed under conventional tillage. Most of the sediment loss was due to snowmelt in years 7 and 9, but to rainfall in year 8.* (Right) *Likewise, the total N and P losses in runoff were very similar for the two watersheds before the tillage system was changed (years 1–4). The loss of nitrogen (green lines) was much greater under conventional tillage (triangle symbols) . Phosphorus losses (blue lines) were greater for conservation tillage (circle symbols), probably because phosphorus applied in that system accumulates near the soil surface.* [Graphed from data in Tiessen et al. (2010)]

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On the other hand, the loss of nutrients by leaching can be somewhat greater with conservation tillage than conventional tillage. In conservation tillage systems, a higher percentage of the precipitation or irrigation water infiltrates into the soil, where it may carry nutrients downward. Over time, many no-till soils develop large macropores (such as worm burrows) that are open to the soil surface. Rain and irrigation water may move down rapidly through these large macropores. However, nutrients held in the finer pores of the soil matrix (as opposed to those on the soil surface) are bypassed by such flow and do not leach into the lower horizons (see Figure 6.29). In such situations, nutrient leaching may actually be less under conservation tillage.

Combining Practices on the Landscape

The most effective solutions to environmental problems often employ the concept of "many little hammers" rather than one big sledge hammer. Thus it may be most efficient to rely on the combined effect of many nutrient management practices deployed sequentially on the landscape. We have discussed the use of nutrient budgets, nutrient cycling, buffer zones, nutrient retaining wetlands, and conservation tillage in isolation. When we put them altogether in an integrated manner, we may find that synergies are realized and resulting nutrient load reductions may exceed the sum of the individual contributions. The concept of integrating many practices sequentially on the landscape to protect water quality from N and P coming from agricultural land is illustrated in Figure 16.13. Engineering and ecological practices that can be sequentially deployed on the land are outlined in Table 16.3.

Nutrient Losses Associated with Forest Management

Undisturbed forests lose nutrients primarily by: (1) leaching and runoff of dissolved ions and organic compounds, (2) erosion of nutrient-containing organic litter and mineral particles, and (3) volatilization of certain nutrients, especially during fires. Most often, the output of such elements as calcium, magnesium, and potassium (but usually not nitrogen) in streams is greater than the input from atmospheric deposition. However, weathering from soil and rock minerals, combined with atmospheric deposition, usually can maintain the plant-available supply of these elements. Nitrogen losses from forested ecosystems commonly range from about 1 to 5 kg/ha each year, while atmospheric inputs of nitrogen (not including biological nitrogen fixation) may be two to three times as great. Annual losses of phosphorus from forest soils are typically very low (<0.1 kg/ha), and are closely balanced by inputs of this element from the atmospheric dust and by slow release from mineral weathering.

Management of forests to produce marketable wood products tends to increase losses by all three pathways just mentioned, plus it adds a fourth very significant pathway, namely, removal of nutrients in forest products (whole trees, logs, or pine straw). Forest management practices that physically disturb the soil (and therefore tend to increase nutrient losses mainly by erosion) include building roads for timber harvesting, dragging

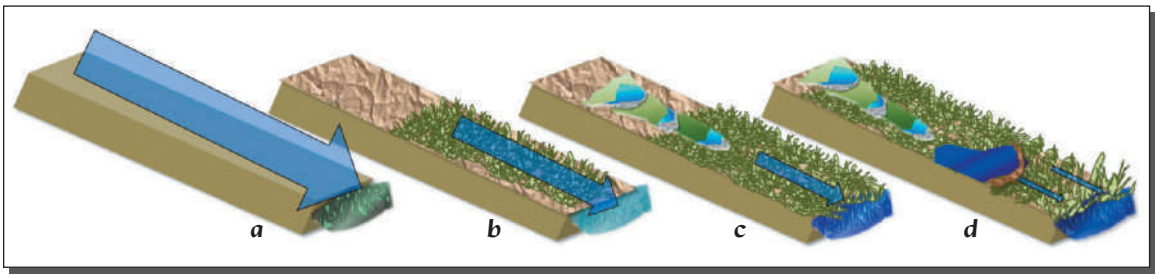

Figure 16.13 *Landscape management to moderate runoff and retain nutrients. (a) With no practices, nutrient and sediment laden runoff flows rapidly to stream. (b) A riparian buffer zone slows the runoff and removes some nutrients. (c) Waterway check dams and contour buffers in the tilled crop field slow and partially clean runoff water before it reaches the riparian buffer. (d) Best results are obtained where the landscape management integrates many practices: conservation tillage and cover crops in the fields, buffers in the waterways, retention wetlands, and riparian buffer zones.* [For more on these concepts, see Kröger et al. (2013)]

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Table 16.3

MANAGEMENT PRACTICES FOR PROTECTION OF WATER QUALITY AT DIFFERENT STAGES OF LANDSCAPE NUTRIENT CYCLES

A complex sequence of practices can act together to reduce nitrogen and phosphorus entering streams and sensitive waters while maintaining the productivity and other ecosystem services of the land. The difference between engineering and ecological approaches may be more distinct in some cases than in others. Explanations for some practices can be found in Chapters 13 and 14.

Sequential steps to nutrient management in the landscape	Solutions for nitrogen (N)		Solutions for phosphorus (P)	
	Engineered	Ecological	Engineered	Ecological
Controlling nutrient inputs to a watershed/ agroecosystem/farm	• Correct the amount of N fertilizer used • Control upwind air pollution to reduce N deposition • Recycle N in human wastes	• Substitute legumes for N fertilizers • Balance livestock and feed production locally • Avoid excess feed protein	• Use phytase to reduce P needed in pig and poultry feeds • Reduce P fertilizer use. • Recycle P in human urine	• Balance livestock and feed production locally • Low phytin feeds with lower total P content • Remove more P in crops and animal products
Distributing nutrients within an agroecosystem/farm	• Variable rate application of fertilizers and manure • Transport manure to fields lowest in N	• PSNT or process model to predict N needed • Controlled grazing to evenly distribute manure/ urine	• Variable rate application of fertilizers and manure • Transport manure to fields lowest in P	• Use soil tests or process model to predict P needed by location • Controlled grazing of livestock to evenly distribute manure/urine
Adjusting solubility/ availability of in-field soil nutrient pools	• Strip tillage to stimulate N release • Iron or alum to reduce NH_3 volatilization • Urease inhibitors • Nitrification inhibitors • Biochar to sorb mineral N	• Adjust soil pH for optimal N cycling • Cover crop residues with varying C/N ratios • Legumes in rotations to reduce fertilizer need • Stabilize manure N by composting	• Add high P-sorption materials, e.g., alum, iron, gypsum, to manure before applying to land • Band or point placement of fertilizer to increase efficiency	• Encourage mycorrhizae that reduce need for added P • Cover crops to cycle P • Stabilize manure P by composting • Use of cover crops with variable C/P ratios
In-field practices to reduce nutrient transport to edge of field	• Terraces • Blind French drains in low spots • Injection of manure (liquid or dry) into soil • Tile drainage control	• Contour planting • No-till or conservation tillage with residue cover • Strip cropping • Cover crops • Grass contour barriers	• Terraces • Apply iron or gypsum to land surface • Inject manure (liquid or dry) into soil • Tile drainage control	• Contour planting • Conservation tillage residue cover • Cover crops • Strip cropping • Grass contour barriers • Pasture management to avoid trampling, erosion
Landscape modification to reduce nutrient delivery from fields to streams	• Check dams and bioretention basins to slow runoff and catch sediment and remove N • Denitrification curtain walls to intercept subsurface nitrate • Biofilters on tile drain outlets to remove nitrate	• Vegetated riparian buffers • Wetland restoration to slow runoff and promote denitrification • Fence cattle out of streams • Provide water for cattle with movable sytems	• Gypsum curtain walls to intercept P dissolved in subsurface drainage • Iron or gypsum ditch filter sorb P from drainage water. • Check dams and basins slow runoff, catch sediment, remove P	• Dense grassy riparian buffers to catch sediment and remove P • Wetlands to slow runoff and catch sediment and remove P

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logs on the ground (skidding), and after-harvest site preparation for planting new trees (see Section 17.9).

Soil Disturbance. Carefully planned tree harvesting and regeneration using methods that minimize soil disturbance and hasten revegetation can keep nutrient losses to low levels. Disturbance of forest soil not only leaves it more vulnerable to erosion, but also can alter the nutrient balance in several other ways. Two practices should generally be avoided, as they can be particularly damaging to the forest nutrient cycle: First, extended suppression of unwanted vegetation with repeated use of herbicides is inadvisable because it delays the repopulation of the soil with active roots (Figure 16.14). Second, windrowing of stumps and slash (tree branches and tops left after harvesting logs) can be detrimental even if it clears land for easy replanting. Organic matter decomposition and mineral nutrient release are accelerated because of physical mixing of the O and A horizons, and a large proportion of site nutrients are concentrated in the area of the windrow, causing less efficient plant use and greater susceptibility to leaching.

Harvest Methods. *Clear-cutting* calls for the simultaneous harvest of all the trees in an area of forestland. This practice is part of *even-aged stand management*, as all the trees in a stand will be planted or will regenerate at the same time. Large openings in the canopy, such as are produced by a clear-cut, are necessary for the regeneration of shade-intolerant species, including many of the most economically important conifers. Having all trees in a stand be of the same age and species simplifies future management (fertilization, thinning, and harvesting can be uniform) and usually maximizes net productivity.

Selective cutting of only a few mature trees at a time confers several advantages. It allows the forest soil to continuously maintain its network of active roots and mycorrhizae, creates only modest disturbance of the forest canopy and landscape appearance, and allows for the maintenance of high species diversity. However, compared to even-aged management, selective cutting is often more difficult to manage, requires the stand to be disturbed with roads and logging equipment more frequently. It is also critically important to avoid removing only the best trees, leaving behind the poorest-quality trees to populate and regenerate the stand.

Whichever harvest strategy is used, it is important to minimize disturbance to the forest floor, during both harvest and regeneration. Leaving slash and stumps in place after a clear-cut harvest encourages an even distribution of nutrients (Figure 16.15). The slash in

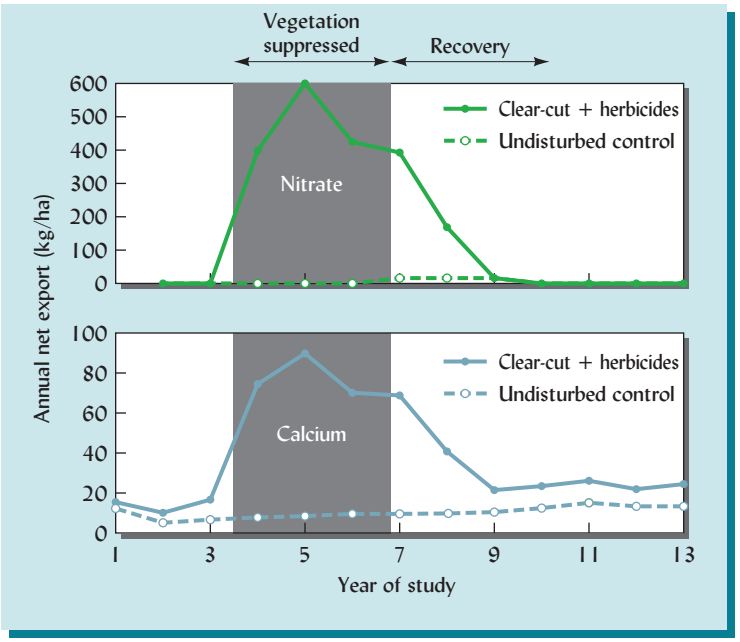

Figure 16.14 *Greatly elevated export of nitrogen and calcium in stream water from an experimental forest watershed where clear-cut harvesting was followed by herbicide suppression of unwanted vegetation for three years. Although the losses shown are about ten times greater than losses reported from other clear-cut watersheds, they amply demonstrate the potential for high nutrient losses when forest ecosystems are drastically disturbed. The extraordinarily high losses were partly due to the nearly nitrogen-saturated condition of this New Hampshire hardwood forest in the United States, and partly to the unusual extended period before living roots were allowed to repermeate the soils and take up nutrients released from litter and slash decomposition.* [Data from Bormann and Likens (1979). © Springer-Verlag]

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Figure 16.15 *Clear-cut harvest of loblolly pine on Coastal Plain soils. A few mature trees were left standing as seed trees. The forest floor is covered with slash of all sizes, but little living vegetation has appeared (one month after harvest in spring). Removal of the tree canopy will allow the sun to warm the soil, accelerating mineralization of nutrients in the forest floor, but decomposition of the high-C/N-ratio slash may immobilize much of the nitrogen released.* (Photo courtesy of Ray R. Weil)

most forests has a very high C/N ratio (see Section 12.3), so its slow decay promotes immobilization and reduces the loss of nitrogen mineralized in the forest floor. On the other hand, when slash has a lower C/N ratio, it may release nitrogen faster than the newly establishing vegetation can use it. This is the case for the nitrogen-fixing red alder forests of the US Pacific Northwest (Figure 16.16), and to a lesser degree for other hardwoods if logged in full summer leaf.

Nutrient Losses. The total amounts of N leaching annually from the uncut forests are very small in comparison to agricultural soils and the preponderance of the dissolved nitrogen lost is in organic forms rather than nitrate. Even where tree harvest uses cable and tower systems that caused minimal physical disturbance to the soils, clear-cutting a forest usually increases litter decomposition and reduces plant uptake, and so greatly increases nutrient leaching, especially for nitrogen (Table 16.4). Streams draining clear-cut watersheds periodically carry elevated levels of nitrogen (including nitrate) and other nutrients for many years after the timber harvest has occurred (Figure 16.17). The concentrations of nitrate-N are usually (but not always) too small (<2 mg N/L) to immediately threaten stream water quality. However, lakes or estuaries into which these streams empty may suffer increased nutrients loads that lead to eutrophication. The loss of nutrients, combined with nutrient removal in the harvested trees, also raises concerns about soil depletion and site productivity, especially on sites that are nutrient-poor to begin with.

Forest Fertilization. Fertilizer application to forests is becoming an increasingly common practice. For example, every year about 1 million hectares of short-rotation slash pine and loblolly pine forests in the southern United States receive applications of N and/or P. These nutrients, along with some sulfur and boron, are also applied widely to forests in the Pacific Northwest. Foresters apply fertilizers for the same reasons that farmers do. Fertilizers prevent soil impoverishment in the face of the nutrient losses just discussed. Application of fertilizer can also raise the fertility level of a site, substantially accelerating plant growth and raising productivity. As might be expected, increases in peak nutrient exports can often be detected when forested watersheds undergo fertilization (Figure 16.18).

Although the effects of forest fertilization on water quality do not yet approach those associated with fertilizer use in agriculture, foresters would be well served to study the lessons

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Figure 16.16 *Clear-cut harvest of a red alder stand on steep Andisols in Oregon, USA. The slash and root mass from this nitrogen-fixing species has a narrow C/N ratio, so mineralization is rapid and nitrogen losses after harvest may be high. In this particular case, the risk of nitrogen loss was increased further because the operator wanted to replant with Douglas fir and therefore planned to use herbicides to suppress weeds and alder regrowth. Note the crawler tractor skidding a log and the truck taking on a load.* (Photo courtesy of Ray R. Weil)

Table 16.4
Dissolved Nitrogen Fluxes Through Soil Profile Layers Under Undisturbed (Uncut) and Clear-Cut (Cut) Mixed Hardwood Forests[a]

The preponderance of the dissolved nitrogen was in organic forms rather than nitrate. The values are the annual total amount of N moving out of the bottom of each layer specified; so much of the N entering from the layer above was apparently retained in some cases. Total amounts (fluxes) of N leaching annually from the uncut forest were very small in comparison to agricultural soils. The forest in the humid temperate southern Appalachian Mountains, USA, was clear-cut harvested using cable and tower system that caused minimal physical disturbance to the soils (Hapludults and Dystrochrepts).

	Uncut	Cut	Uncut	Cut	Uncut	Cut	Uncut	Cut	Uncut	Cut
	Dissolved organic N		Ammonium-N		Nitrate-N		Total dissolved N		DON of total	
Soil horizon	kg ha^{-1}								— % —	
Oa	3.29	11.64	0.69	2.65	1.57	0.14	5.55	14.43	59	81
A	1.98	15.12	0.39	1.29	1.01	0.61	3.38	17.02	59	89
AB	1.59	4.49	0.13	0.18	0.05	0.05	1.77	4.72	90	95
B	0.33	0.91	0.04	0.06	0.02	0.27	0.39	1.24	85	73
C	0.06	0.10	0.02	0.03	0.02	0.03	0.10	0.16	62	61

[a]From selected data in Qualls et al. (2014).

learned from fertilizer use on farms and so avoid making the nutrient management mistakes that have plagued agriculture.

In the remainder of this chapter we will concentrate on the properties and uses of various nutrient sources, on the measures designed to meet the goals of nutrient management outlined in the preceding, and on methods of assessing plant and soil nutrient status in order to determine which nutrients need to be supplemented and in what quantities.

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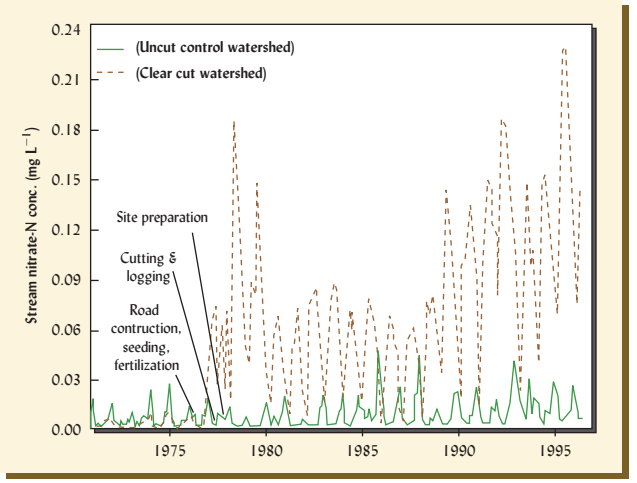

Figure 16.17 *Mean monthly nitrate-N concentrations in stream water from two commercial forested watersheds in North Carolina, USA. Data are shown for a calibration period when both watersheds were managed identically (1971–1976), a treatment period (1976–1977) when one watershed was clear-cut and replanted, and a postharvest period (1978–1996) when both watersheds were left undisturbed. Nitrate-N concentrations increased in the logged watershed and continued to be higher even after 20 years of regrowth, suggesting that nutrient-recycling processes were disrupted in some fundamental way. However, when concentrations were multiplied by stream flow volume (not shown) to calculate nitrate-N mass losses, the differences between watersheds were relatively small, nitrate-N losses in the logged watershed ranging from 0.25 to 1.27 kg N ha^{-1} yr^{-1} more than the control watershed during the first five years after logging. These differences can be compared to 4.5 kg N ha^{-1} yr^{-1} received in atmospheric deposition.* [Redrawn from Swank et al. (2001)]

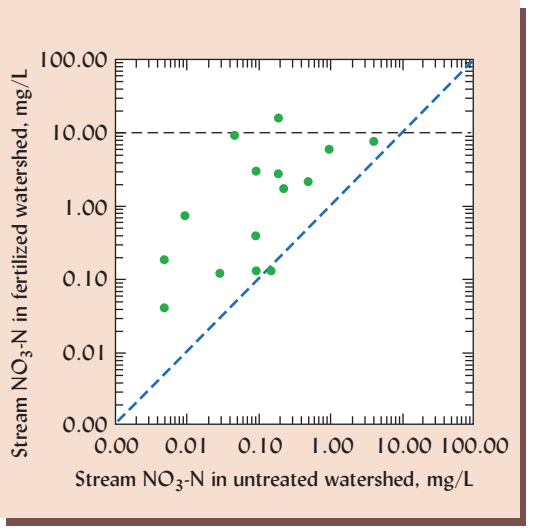

Figure 16.18 *Short-term peak nitrate-N (NO_3–N) concentrations in streams draining forested watersheds with or without application of 200–250 kg N/ha as urea fertilizer. Each data point represents one pair of watersheds (fertilized versus untreated). The diagonal dashed line represents no treatment effect; points above the line indicate increased nitrate-N concentration compared to the control. Note that log scales are used because the range of concentrations among watersheds is very large (0.003–20). In all but two of the watersheds, fertilizing the forest substantially increased peak nitrate concentrations in the stream water, in some cases to more than 10 mg/L. As in agriculture, best management practices are necessary in forestry to protect environmental quality while increasing plant productivity.* [Data from a survey of research results in Brown and Binkley (1994); see also Binkley et al. (1999)]

16.3 NATURAL ECOSYSTEM NUTRIENT CYCLES

Internal nutrient resources come from within the ecosystem, be it a forest, a watershed, a farm, or a home in the suburbs, and are generally preferred, since their financial and environmental costs are minimized. These resources include the process of mineral weathering within the soil profile, biological nitrogen fixation, acquisition of nutrients from atmospheric deposition, and various forms of internal recycling, such as utilization of cover crops, retention of plant residue, and application of animal manure to the fields that grew the animal feed.

If internal resources prove inadequate, nutrients must be imported from resources external to the system, (see Section 13.15). Such *external* resources are usually purchased inorganic or organic fertilizers. Various types of organic residues and (so-called) wastes are available to be used on land as a source of supplemental nutrients (and organic matter). Among the most plentiful and most commonly used to enhance soil fertility are the crop residues and animal manures already mentioned. In addition, municipal refuse rivals animal manure in terms of its quantity and nutrient content, but only about 10% or so is composted and applied to land. More than half of sewage sludge and septage (sludge from septic tanks, see Section 6.8) is used as a soil amendment, but the total quantity is much smaller than animal manures. Organic

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wastes from food processing and other industries, as well as certain logging and wood manufacture wastes also offer some (mostly unrealized) potential as soil amendments. For most suburban homeowners, all the nutrients their landscaping and gardens might require could usually be supplied by collecting (instead of using drinking water to flush away) the residents' urine (see Box 20.2 for details).

Depending on the parent materials and climate, weathering of minerals (see Section 2.1) may release significant quantities of nutrients (Table 16.5). For timber production, most nutrients are released fast enough from either parent materials or decaying organic matter to supply adequate nutrients. In agricultural systems, however, some nutrients generally must be added, since nutrients are removed from the land annually in harvested crops. Negligible amounts of nitrogen are released by weathering of mineral parent materials, so other mechanisms (including biological nitrogen fixation) are needed to resupply this important nutrient. Release of nutrients by mineralization of soil organic matter is important in short-term nutrient cycling, but in the long run, the organic matter and the nutrients it contains must be replenished or soil fertility will be depleted.

Nutrient Economy of Forests[3]

Forest productivity depends on many factors such as rainfall, temperatures, microclimates, soil water holding capacity, diseases, pests and tree species, as well as management practices such as stand thinning, planting, and harvesting. The availability of plant nutrients from soils (or from atmospheric deposition in the case of N, S, and Ca) also plays a role. In fact, in some forests, soil fertility may override the other influences just named, such that tree growth (expressed as net ecosystem primary productivity, NEP) is limited by the low availability of one or more nutrients. Globally, forests on infertile soils tend to be much less efficient users of carbon and solar energy because they respire back to the atmosphere a larger proportion of the carbon fixed by photosynthesis (Figure 16.19).

Recycling. In most forests, organic matter mineralization is the main source of nutrients for tree growth, and the rates of nutrient uptake from the soil by the trees closely match the rates of release by mineralization. Surface plant litter makes up but a small proportion of the nutrients cycled from trees to the soil decomposers each year. The biggest portion comes from a combination of fine roots and mycorrhizal hyphae (see Sections 11.7 and 11.9). A second major source of nutrients for each season's tree growth is the recycling process within the trees themselves. Nutrients are translocated from the leaves to the twigs and branches just prior to

Table 16.5
NUTRIENT RELEASE BY MINERAL WEATHERING IN A REPRESENTATIVE HUMID, TEMPERATE CLIMATE, COMPARED WITH REMOVAL BY HARVEST OF TREES OR CROPS
For the forest, weathering release and harvest removal are roughly balanced, but cropping removes much more of some nutrients than can be released by weathering. Leaching losses are not shown.

	Amount released or removed, kg/ha			
	P	K	Ca	Mg
Weathered from igneous parent material over 50 years	5–25	250–1000	150–1500	50–500
Removed in harvest of 50-year-old deciduous bole wood	10–20	60–150	175–250	25–100
Removed by 50 annual harvests of a corn–wheat–soybean rotation	1200	2000	550	500

Estimated from many sources.

[3]For in-depth treatments of this topic, see Perry (1994) and Likens and Bormann (1995). Aber et al. (2000) provide insights on ecological challenges in forestry.

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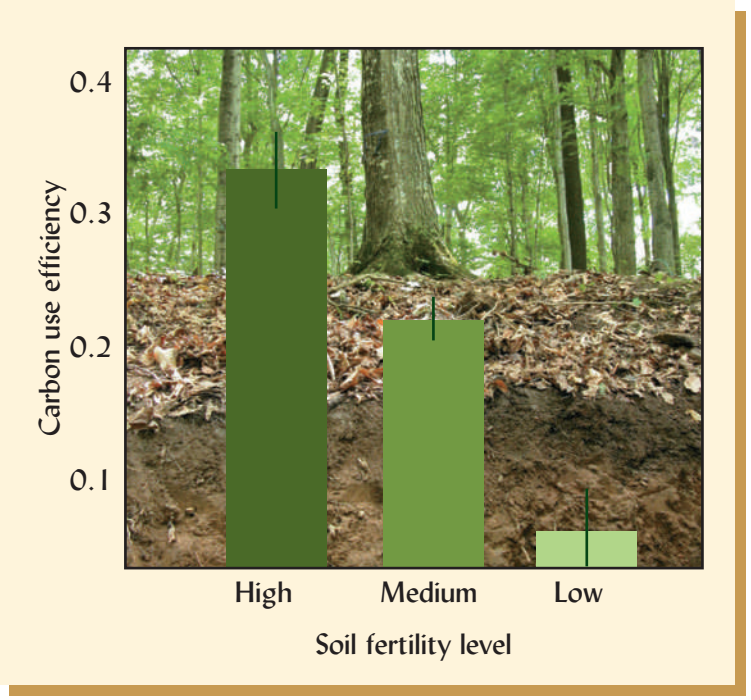

Figure 16.19 *Nutrient availability in forest soils (but not forest management) largely controls the ability of trees to mitigate climate change by sequestering carbon. This is the conclusion from a review of research on 92 forests around the world. Fertile soil not only increased photosynthesis, but also reduced respiration loss of C per unit of C photosynthesized. The ecosystem carbon use efficiency (CUE) equals the ratio of net ecosystem productivity (NEP, the rate C is stored as biomass after accounting for the return of C to the atmosphere by plant respiration) divided by the gross primary production (GPP, the rate at which photosynthesis removes C from the atmosphere): CUE = NEP/GPP. In forests with low fertility soils, a much larger proportion of GPP was released through ecosystem respiration, resulting in lower CUE. The forests were classified into high, medium, and low soil fertility groups based on N and P concentrations in plant tissue and soil, soil texture, soil pH, soil C/N ratio, N deposition, soil mineralization rates, and other data indicating the degree to which productivity was limited by soil nutrients.* [Based on data in Fernandez-Martinez et al. (2014); photo courtesy of Ray R. Weil]

litter fall. The translocated nutrients are then remobilized early in the next growing season to produce new leaf growth and wood increment. Additional sources are atmospheric deposition and weathering of soil minerals.

Forests have evolved several mechanisms to conserve nutrients in nutrient-poor sites. For instance, conifers in cold regions (e.g., black spruce) may retain their needles for several decades rather than shed them more frequently, enabling these trees to grow on sites with very low levels of nitrogen availability (the needles are much higher in nitrogen than the woody tissues). Forests generally produce more aboveground biomass (100–200 kg) per kilogram of nitrogen taken up than other ecosystems (e.g., corn produces about 60–70 kg biomass per kg N taken up). In cold climates or in coniferous forests, slow rates of organic matter decomposition result in the immobilization of the system's nitrogen in the forest floor (Table 16.6).

Surface Soil Enrichment. Forest trees obtain most of their nutrients from the surface horizons, but trees are also well adapted to gathering nutrients from deep in the soil profile, where much of the nutrient release from parent material takes place. Overall nutrient-use efficiency can sometimes be increased by combining trees and annual agricultural crops into what are known as *agroforestry systems* (Figures 16.20 and 20.25).

Trees can improve fertility of the upper soil horizons in several ways. In Chapter 2 (Figure 2.27) we saw that trees can act as nutrient pumps, altering the course of soil formation. Tree roots can take up nutrients deep in the profile where they occur because of weathering or leaching. Then as the tree leaf and root litter decomposes the nutrients are released into the A horizon where they can be of use to relatively shallow-rooted agricultural crops. Nitrogen-fixing trees (mostly legumes) can also add nitrogen from the atmosphere to the surface soil with their nitrogen-rich leaf litter. Trees may also enhance the fertility of the soil in their vicinity by trapping windblown dust and by providing shade and shelter for birds and animals that leave their droppings near the trees.

Some Effects of Fire

In hot-burning forest wildfires, most of the nitrogen and sulfur and some of the phosphorus in the burned biomass convert into gaseous forms in which they are lost from the site. For

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Table 16.6
REPRESENTATIVE NUTRIENT DISTRIBUTION IN SEVERAL TYPES OF FOREST ECOSYSTEMS[a]

	In vegetation, kg/ha	In forest floor, kg/ha	Residence time,[b] years
		Nitrogen	
Boreal coniferous	300–500	600–1100	100–300
Temperate deciduous	100–1200	200–1000	5–7
Tropical rain forest	1000–4000	30–50	0.4–0.8
		Phosphorus	
Boreal coniferous	30–60	75–150	150–450
Temperate deciduous	60–80	20–100	4–8
Tropical rain forest	200–300	1–5	0.4–0.8
		Potassium	
Boreal coniferous	150–350	300–750	50–150
Temperate deciduous	300–600	50–150	0.8–1.5
Tropical rain forest	2000–3500	20–40	0.1–0.3
		Calcium	
Boreal coniferous	200–600	150–500	100–200
Temperate deciduous	1000–1200	200–400	2–4
Tropical rain forest	3500–5000	100–200	0.2–0.4

[a]Data derived from many sources.
[b]Residence time in forest floor (O horizons).

Figure 16.20 *Two examples of agroforestry systems.* (Left) *The deep-rooted* Faidherbia (Acacia) albida *enriches the soil under its spreading branches (note man in white shirt). Conveniently, these trees lose their leaves during the rainy season when crops are grown, so the trees do not compete with crops for light. Africans traditionally leave these trees standing when land is cleared for crop production. Crops growing under the trees yield more and have higher contents of sulfur, nitrogen, and other nutrients.* (Right) *Branches pruned from widely spaced rows of leguminous trees are spread as mulch in the alleys between the tree rows, thus enriching the alley soil with nutrients from the leaves as well as conserving soil moisture. Crops grown in this alley-cropping system may yield better than crops grown alone, but only if competition between trees and crop plants for light and water can be kept to a minimum.* (Photos courtesy of Ray R. Weil)

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several years after a high-intensity burn, there may continue to be increased amounts of P in runoff (see Figure 14.9). Ashes, both from wildfires and from prescribed burns (low-intensity intentional fires), contain high levels of soluble K, Mg, Ca, and P. Thus, fire increases the short-term availability of these nutrients, but also increase their rate of loss from the forest ecosystem. Wildfires usually result in greater nutrient losses than do prescribed burns, because the high heat associated with wildfires destroys some of the organic matter of the soil as well as the aboveground biomass.

Nutrient Cycling in Grasslands

The burning of rangeland grasses (or crop residues) usually produces much less volatilization of nitrogen and sulfur than do forest wildfires, as grass fires move quickly and burn at relatively low temperatures. While the loss of organic matter consumed by the fire is undeniable, the release of nutrients and the increased light penetration with the opening up of the grass canopy may stimulate plant biomass production, especially belowground. As a result, organic matter accumulation may be greater under grasslands that experience occasional burns than under those where fire is completely controlled. Grazing by large mammals, if not too frequent and sustained, can also stimulate increased plant production and quality (Box 16.1). Fire and grazing, both natural components in rangeland ecosystems are important tools for managing nutrient cycles and soil productivity.

16.4 RECYCLING NUTRIENTS THROUGH ANIMAL MANURES[4]

For centuries, the use of farm manure has been synonymous with successful and stable agriculture. In this context, manure supplies organic matter and plant nutrients to the soil and is associated with the production of soil-conserving forage crops used to feed animals. About half of the solar energy captured by plants grown for animal feed ultimately is embodied in animal manure, which if returned to the soil can be a major driver of soil quality.

Huge quantities of farm manure are available each year for the recycling of essential elements to the land. For each kilogram of liveweight, farm animals produce approximately 2–4 kg dry weight of manure per year. In the United States, the farm animal population voids some 350 million Mg of manure solids per year, about ten times as much as does the human population. Some manure is spread on pastures by grazing animals, while about 20% is excreted in a manner that allows its collection for use as a soil amendment. The US Department of Agriculture estimates that about 5% of US cropland is treated with livestock manure in any given year.

Nutrient Composition of Animal Manures

Generally, about 75% of the N, 80% of the P, and 90% of the K ingested by animals pass through the digestive system and appears in the manure (including urine). For this reason, animal manures are valuable sources of both macro- and micronutrients. Nutrient content varies greatly from one type of animal manure to another (e.g., poultry manure compared to horse manure). For a particular type of animal, the actual water and nutrient content of a load of manure will depend on the nutritional quality of the animals' feed, how the manure was handled, and the conditions under which it has been stored (Tables 16.7 and 16.8). Therefore, it is wise to regularly obtain laboratory analyses of the value of the particular manure in question rather than rely on general statements and textbook information.

Both the urine (except for poultry, which produce solid uric acid instead of urine) and feces are valuable components of animal manure. On average, a little more than *one-half of the N*, about *90% of the P*, and about *40% of the K* is found in the solid manure. Nevertheless, this higher nutrient content of the solid manure is offset by the more ready availability of the

[4]Some of the challenges of such recycling are discussed in Gardner (1997) and a wide range of European perspectives on manure management in modern industrial agriculture can be found in Sommer et al. (2013). Hilimire (2011) reviews livestock-cropping integration in the USA.

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BOX 16.1

GRAZING MAMMALS AND NUTRIENT CYCLING IN SOILS

Most tourists don't travel to East Africa to see the amazing diversity of soils; most come to see wildlife in their natural habitat. However, in the vast Serengeti plains, variations in soil fertility do influence where one finds nonmigratory antelopes and gazelles - and the lions and cheetahs that prey on them. These animals graze most frequently where soils are relatively high in nitrogen and sodium, two mineral nutrients critical to health and survival, especially of pregnant or lactating females and their young (Figure 16.21). The animals not only seek out more fertile soils, they also help enhance the fertility of the soils they frequent. The animals leave manure and urine that contain most of the nutrients they consumed, but in a more easily decomposable form than in the original plant material. Also, animals' grazing seems to stimulate vigorous growth of palatable, easily decomposed plant species, thus speeding the cycling of nutrients. Nitrogen concentrations in plant regrowth after grazing generally are higher than in ungrazed plants, making the resulting plant residues more readily recyclable in the soil.

*Over*grazing, however, is not such a good thing. It occurs when density and frequency of grazing exceeds the *carrying capacity* of the land. Continual heavy grazing or other forms poorly managed grazing by livestock may kill off the most palatable species, so that the vegetation becomes relatively sparse and dominated by less palatable plants. In some cases, the residues of these plants are also less decomposable. The resulting impairment of the nutrient cycling processes accelerates the deterioration of the vegetative cover and exposes the soil to the erosive action of wind and water (see Section 17.11).

The use of grasslands for grazing (pastures) contrasts sharply with the use of similar grasslands to produce hay. Hay is vegetation that has been mechanically cut, preserved by sun-drying, and then bailed and removed from the land to feed livestock in another time and place, as needed. Harvesting hay removes large amounts of nutrients that are *not* returned by grazing animals in urine and feces. Thus, hayfields usually require the addition of large amounts of nitrogen and potassium (and smaller amounts of other nutrients) to partially replace nutrients removed in harvest. On the other hand, a well-grazed pasture should not be fertilized as if it were a hayfield. Grazing animals typically recycle back to the soil most of the nutrients taken up by the vegetation so properly grazed pastures rarely need fertilizer. In fact, fertilization of grazed pastures may lead to excess phosphorus in runoff water and to excessive leaching of nitrogen (Figure 16.22). Of course, some fields may be both grazed and harvested for hay, and need to be managed accordingly.

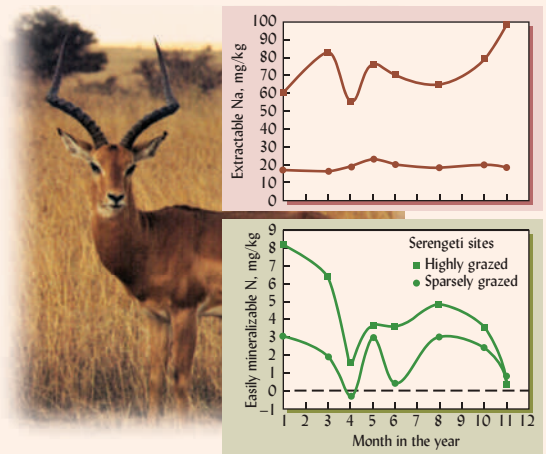

Figure 16.21 *Grazing mammals interact with soil in the east African Savannah. Soil sodium (upper) and nitrogen (lower) where gazelles habitually graze heavily or sparsely. Averages for two pairs of sites and two years in Tanzania's Serengeti savannah.* [Nyle C. Brady and Ray R. Weil]

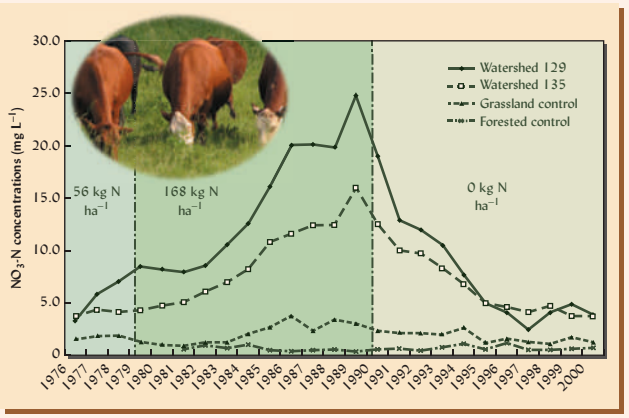

Figure 16.22 *Nitrate leaching caused by fertilizing grazed grasslands in a temperate humid region (Ohio, USA). Watersheds 129 and 135 were rotationally grazed with beef cattle. The other two watersheds (controls) were not grazed, fertilized, or harvested. When N fertilization was increased from 56 to 168 kg ha^{-1} yr^{-1}, groundwater NO_3-N changed little in the first few years, but then increased for ten years. The NO_3-N concentrations returned to low levels within six years after discontinuation of N fertilization, even though legumes were interseeded into the grasslands.* [Data from Owens et al. (2008); photo courtesy of Ray R. Weil]

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Table 16.7
INFLUENCE OF HANDLING AND STORAGE METHODS ON NUTRIENT LOSSES FROM ANIMAL MANURE BETWEEN EXCRETION AND APPLICATION TO LAND

Manure handling and storage method	Percentage lost		
	N	P	K
Solid systems			
Daily scrape and haul	15–35	10–20	20–30
Manure pack or compost	20–50	5–10	5–10
Liquid systems			
Aerobic tank storage	5–25	5–10	0–5
Lagoon (anaerobic) storage	70–80	50–80[a]	50–80

[a]Most of the P and K in a lagoon system is recoverable only when the sludge is dredged out.
From Sutton (1994).

Table 16.8
EXAMPLE OF THE VARIABLE COMPOSITION OF FARM MANURE
The data are based on 28 samples of horse manure sent in to one lab over a period of five years.

	Percent of fresh weight				
	Total N	Soluble N	P	K	Water
Lowest analysis	0.21	0.0	0.04	0.07	39
Highest analysis	0.85	0.14	0.75	1.0	80
Average analysis	0.51	0.03	0.16	0.35	63

Courtesy from University of Maryland Soil Test Lab

constituents carried by the urine. Effective nutrient conservation requires that manure handling and storage minimize the loss of the liquid portion.

The data in Table 16.9 show that manures and most other organic nutrient sources have a relatively low nutrient content in comparison with commercial fertilizer. On a dry-weight basis, animal manures contain from 2 to 5% N, 0.5 to 2% P, and 1 to 3% K. These values are one-half to one-tenth as great as are typical for commercial fertilizers.

Furthermore, manure is rarely spread in the dry form, but usually contains a great deal of water. As it comes from the animal, the water content is 30–50% for poultry to 70 or 85% for cattle (see Table 16.9). If the fresh manure is handled as a solid and spread directly on the land high water content is a nuisance that adds to the expense of hauling. If the manure is handled and digested in a liquid form or slurry and applied to the land as such, even more water is involved (Figure 16.25, *right*). All this water dilutes the nutrient content of manure, as normally spread in the field, to values much lower than those cited for dry manure in Table 16.9. The high content of water and low content of nutrients makes it difficult to economically justify transporting bulk manure to distant fields where it might do the most good. However, the value of the micronutrients in manure (Table 16.9) and the additional benefits of its organic matter (see Section 12.5) may be even greater than that of its N—P—K content, and should be included in any economic evaluation of manure transport.

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Table 16.9

COMMONLY USED ORGANIC NUTRIENT SOURCES: THEIR APPROXIMATE NUTRIENT CONTENTS AND OTHER CHARACTERISTICS

Along with nitrogen-fixing legumes grown in rotation and as cover crops, materials such as these (except sewage sludge and municipal solid wastes) provide the mainstay of nutrient supply in organic farming. The nutrient contents shown for animal manures are typical of well-fed livestock in confinement production systems. Manure from free-range animals not given feed supplements may be considerably lower in both nitrogen and phosphorus.

	% [a]	Percent of dry weight						g/Mg of dry weight						
Material	Water	Total N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Mo	
Coffee grounds[b]	60	1.6	0.01	0.04	0.08	0.01	0.11	330	50	15	40	—	—	May acidify soil.
Cottonseed meal	<15	7	1.5	1.5	—	—	—	—	—	—	—	—	—	Acidifies soil. Commonly used as livestock feed.
Dairy cow manure[c]	75	2.4	0.7	2.1	1.4	0.8	0.3	1,800	165	165	30	20	—	May contain high-C bedding.
Dried blood	<10	13	1	1	—	—	—	—	—	—	—	—	—	Slaughterhouse by-product, N available quickly.
Dried fish meal	<15	10	3	3	—	—	—	—	—	—	—	—	—	Incorporate or compost due to bad odors. Can feed to livestock.
Feedlot cattle manure[d]	80	1.9	0.7	2.0	1.3	0.7	0.5	5,000	40	8	2	14	1	May contain soil and soluble salts.
Hardwood tree leaves[e]	20	1.0	0.1	0.4	1.6	0.2	0.1	1,500	550	80	10	38	—	High Pb for some street trees.
Horse manure[d]	65	1.4	0.4	1.0	1.6	0.6	0.3	—	200	125	25	—	—	May contain high-C bedding.
Municipal solid waste compost[f]	40	1.2	0.3	0.4	3.1	0.3	0.2	14,000	500	650	280	60	7	May have high C/N, heavy metals, plastic, and glass.
Poultry (broiler) manure[c]	35	4.4	2.1	2.6	2.3	1.0	0.6	1,000	413	480	172	40	0.7	May contain high-C bedding, high soluble salts, arsenic, and ammonia.
Sewage sludge, activated	<10	6	1.5	0.5	2.0	—	2.0	40,000	—	450	—	—	—	e.g. Milorganite®, N released 2–6 months, low solubility P, low salt index. Poor on cold soil.
Sewage sludge, digested	80	4.5	2.0	0.3	1.5[g]	0.2	0.2	16,000[g]	200	700	500	100	15	May contain high soluble salts, toxic heavy metals, pharmaceuticals.
Sheep manure[d]	68	3.5	0.6	1.0	0.5	0.2	0.2	—	150	175	30	30	—	
Spoiled legume hay	40	2.5	0.2	1.8	0.2	0.2	0.2	100	100	50	10	1,500	3	May contain weed seeds.
Swine manure[d]	72	2.1	0.8	1.2	1.6	0.3	0.3	1,100	182	500	300	75	0.6	May contain elevated Cu and Zn.
Wood wastes	—	—	0.2	0.2	0.2	1.1	0.2	2,000	8,000	500	50	30	—	Very high C/N ratio; must be supplemented by other N.
Young rye green manure	85	2.5	0.2	2.1	0.1	0.05	0.04	100	50	40	5	5	0.05	Nutrient content decreases with advancing maturity.

[a]Water content given for fresh materials. Processing and storage methods may alter water content to less than 5% (heat dried) or to more than 95% (slurry).
[b]Coffee grinds data from Krogmann et al. (2003).
[c]Broiler and dairy manure composition estimated from means of ~ 800 and 400 samples analyzed by the University of Maryland manure analysis program 1985–1990.
[d]Composition of swine, sheep, and horse manure calculated from Zublena et al. (1993) and Cu and Zn in swine averaged from other sources.
[e]Hardwood leaf data from Heckman and Kluchinski (1996).
[f]Composition of municipal solid waste compost based on mean values from ten composting facilities in the United States as reported by He et al. (1995). Sulfur as sulfate-S.
[g]Sludge contents of Ca and Fe may vary tenfold depending on the wastewater treatment processes used.

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Potential Environmental Consequences of Manure Utilization

The disposal or utilization of manure results in environmental consequences that range from very localized to global impacts. Local impacts include odors (mainly from ammonia NH_3 and sulfurous gases), runoff containing nutrients, organic matter, and fecal pathogens that pollute local streams, ponds, and lakes, and the accumulation of heavy metals and pharmaceuticals in farm soils (and possibly in the produce harvested from the land). More widespread regional impacts include pollution of major rivers and estuaries by leaching and runoff loss of N and P, pharmaceuticals, hormones, and other chemicals. The most truly global impacts stem mainly from emissions of greenhouse gases (NO_x, NH_3, CH_4).

An additional issue of concern for manure from poultry and swine concentrated animal-feeding operations (CAFOs) is the presence of very high levels of copper, zinc or arsenic, as these elements are commonly added to pig diet in amounts far in excess of the animals' nutritional needs. Copper is added to control bacteria in the pig gut and promote faster growth, while feeds are also commonly fortified with zinc to reduce problems known as *postweaning scours*.

Concentrated Animal-Feeding Operations

In most industrialized countries, the advent of huge, CAFOs and the separation of crop production from livestock production have changed the perception of animal manure from an *opportunity for recycling nutrients and organic matter* as efficiently as possible to an *obligation for disposing of wastes* with as little cost and environmental damage as possible (Figure 16.23). If manure-holding and disposal practices are inadequate, waters under or near such CAFOs may become polluted with nitrates and pathogens, and water from nearby wells may be unfit to drink (Table 16.10).

Cattle Feedlots. More than two-thirds of US feedlot beef production takes place on "farms" that have no cropland at all. To visualize the enormity of the manure disposal problem, consider a 100,000-head beef feedlot. We can estimate that the feedlot produces 200,000 Mg of manure (dry matter) per year:

$$\frac{(4\ \text{Mg manure})}{\text{Mg liveweight}} \times \frac{0.5\ \text{Mg liveweight}}{\text{animal}} \times 100{,}000\ \text{animals} = 200{,}000\ \text{Mg manure}$$

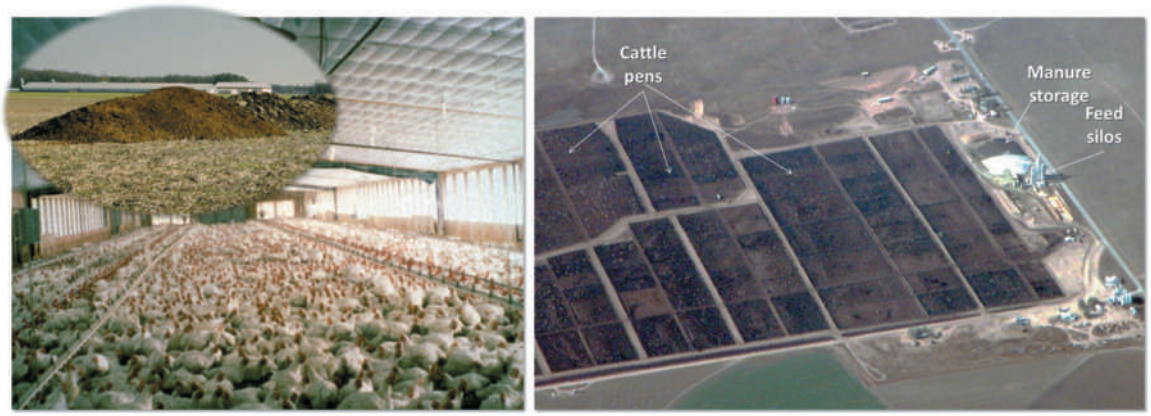

Figure 16.23 *Examples of concentrated animal feeding operations (CAFOs). Interior of broiler chicken house in Maryland, USA, with an inset showing an exterior view of a pile of manure cleaned out from such a house. (*Right*) An aerial view of a large cattle feedlot in Colorado, USA. In both types of CAFOs animals are fed on grain imported from distant farms. It is difficult for such CAFOs to recycle nutrients in the manure back to the land on which the cattle feed was grown. Instead of being seen as a valued resource, the manure in this situation may be considered a troublesome waste to be disposed of. Agriculture is challenged to structure itself in a more ecologically balanced manner that better integrates its animal and crop components.* (Photos courtesy of Ray R. Weil)

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Table 16.10
SOIL AND SITE CHARACTERISTICS INFLUENCING THE LIKELIHOOD OF NITRATE CONTAMINATION OF WELLS IN MIDWESTERN USA
Sites with sandy soils, near cropland, near barnyards, and having shallow wells had the highest nitrate-N levels and the greatest percentage of well exceeding the 10 mg/L limit considered suitable for human consumption.

Characteristics	Texture of soils		Proximity to cropland		Proximity to feedlot or barnyard		Well depth		Shallow wells near barnyard or feedlot
	Sandy	Clayey	<6 m	Out of sight	<6 m	Out of sight	Deep >30 m	Shallow <15 m	
No. of wells	2412	6415	1684	3098	704	7520	5106	3467	158
Percent with NO_3-N >10 mg/L	7.2	3.1	6.4	1.8	12.2	2.8	1.1	9.7	25.3

Data from Richards et al. (1996).

If this manure contains 2% N and the corn grain grown to feed the cattle removes some 140 kg N/ha, then we can estimate that the manure should be applied at 7 Mg/ha (~3 tons/acre),[5]

$$\frac{1\ \text{Mg manure}}{0.02\ \text{Mg N}} \times \frac{140\ \text{kg N}}{\text{ha}} \times \frac{1\text{Mg}}{1000\ \text{kg}} = \frac{7\ \text{Mg manure}}{\text{ha}}$$

and that utilization of the manure in this manner would require some 28,000 ha of land,

$$\frac{(1\ \text{ha})}{7\ \text{Mg manure}} \times 200{,}000\ \text{Mg manure} = 28{,}571\ \text{ha}$$

If the corn were grown in rotation with soybean (a legume crop that does not need applied N), then the total amount of cropland required for manure utilization would double to 34,000 ha or 340 km^2. To find this much cropland, some of the manure would have to be hauled 20–50 km or more from the feedlot! Finally, if soil phosphorus is already at (or above) optimal levels from previous manuring, as is usually the case near CAFOs (Section 14.9), manure should be applied at a much lower rate tailored to meet the P (not N) needs of the crops, thus requiring an even larger land base.

In the absence of sufficient education and enforced regulation, managers unsurprisingly tend to save transportation costs and time by applying manure to nearby fields at higher-than-needed rates. Applications at such high rates typically result in the pollution of surface and groundwater by nitrogen and phosphorus and may cause salinity damage to crops and soils.

Poultry and Swine Manure. Even more concentration of nutrients exists in the poultry and swine industries. Nearly all chickens and most hogs produced in the United States are grown in large CAFOs located near meat-processing plants. Not only do such CAFOs import nutrients in feed grains, but they also import calcium-P mineral feed supplements to compensate for the inability of their nonruminant animals to digest *phytic acid*, the form of P found in most seeds (see Section 14.4). The manure produced therefore contains more nitrogen and far more phosphorus than the local cropland base can properly utilize (see Figures 16.1–16.3). As a result, farm fields near large CAFOs tend to have very high levels of N and P in both the soil and in the water draining from the land.

[5]In the unlikely event that the land had not been previously manured, some N fertilizer might be needed for the corn silage in the first year or two to supplement the N released from the manure, but soon N released from previous years' applications would make supplementary fertilizer unnecessary (see Section 16.9).

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Some Stop-Gap Measures. Although probably not long-term solutions to an unbalanced agricultural system, the public welfare may be served by such approaches as the following: (1) Discourage further manure applications to fields already saturated with nutrients; instead, facilitate transportation of manure to areas with low P soils. (2) Encourage the use of new corn varieties that contain less phytic acid P and more inorganic P, allowing better assimilation by nonruminant animals and making it less necessary to purchase P feed supplements, thereby reducing the amount of P excreted. (3) Promote manure composting to reduce the volume of material and the solubility of the nutrients in it. (4) Eliminate the overfeeding of P supplements to all types of livestock, in order to reduce the concentration of P in the manure (Figure 16.24). (5) Mix iron or aluminum compounds with the manure to reduce the solubility of its phosphorus (see Section 14.5).

Storage, Treatment, and Management of Animal Manures

Integrated Animal Production. Where animal and crop production are integrated on a farm, manure handling is not too much of a problem. The use of carefully managed pasture for cattle can be maximized so that the animals themselves spread most of the manure and urine while grazing. The total amount of nutrients in the manure produced on the farm is likely to be somewhat less than that needed to grow the crops; thus, modest amounts of inorganic fertilizers may be needed to make up the difference.

Manure Handling in Confinement Systems. Where animals are concentrated in large confinement systems, the problem of manure disposal takes precedence over its utilization. The nutrient content of the manure can be markedly affected by the handling methods used (Table 16.7). Most types of manure storage cause considerable N loss to the atmosphere, as just mentioned, while most of the P and K remain in the manure lagoon or compost pile. These changes during storage thus lower the N/P ratio in the manure, making it more difficult to utilize the manure as a N source without over applying P.

The manure can be collected and *spread daily*, *packed in piles* where it is allowed to partially decompose before spreading, stored in *aerated ponds* that promote oxidation of the organic materials, or stored in deep *anaerobic lagoons* in which the manure ferments in the absence of oxygen gas. The latter method produces several environmentally damaging gases: methane (a powerful greenhouse gas that should be captured to use as fuel) and ammonia (which contributes to acrid odors and nitrogen deposition) are gaseous products of fermentation, while nitrogen gases (including NO and N_2O which are also powerful greenhouse gasses) are produced by denitrification. Storage and microbial processing of manure in composting piles or in liquid slurry lagoons for several months before spreading on the land can greatly reduce the potential for contaminating fruits and vegetables with pathogens that can cause human illness.

Methods of manure handling that both prevent pollution and preserve nutrients, especially N, in a form that can be easily transported and sold commercially would make a major

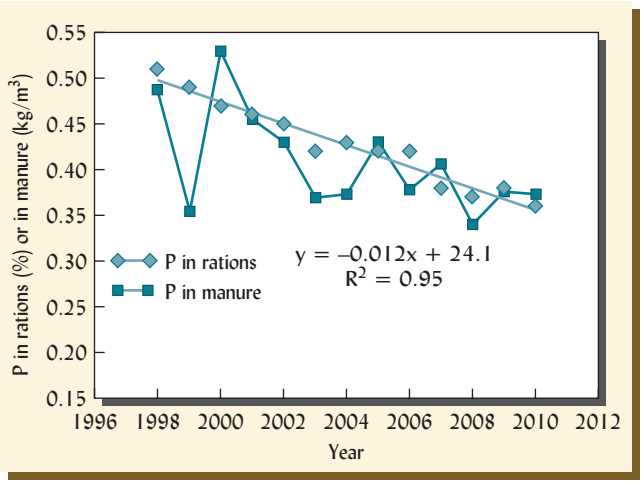

Figure 16.24 *More careful formulation of animal feed can help reduce nutrient pollution from farm manure. The decline in P content of liquid dairy manure from commercial farms in Wisconsin paralleled the reduction of P in the total mixed rations fed to dairy cows on Wisconsin farms in the United States. The reduced P in the rations during a 12 year period resulted from a concerted effort to address concerns about phosphorus water pollution stemming from manure spread on dairy farmland. The graph is based on analyses of nearly 15,000 samples of liquid dairy manure.* [Graphed from data of University of Wisconsin Extension (Peters, 2012)]

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contribution to ameliorating the manure problem for concentrated animal production enterprises. Options currently being developed include the following: (1) **Heat-dry** and **pelletize** technology transforms the sloppy manure into small pellets that handle like commercial fertilizer. Although expensive in terms of energy and capital, the product is popular in the landscaping and lawn industries as a slow-release fertilizer. (2) Dry and heat the manure to high temperatures with limited oxygen to **pyrolize the manure and form a biochar** that is easy to handle, may be profitable to ship to areas where nutrients are needed, and may enhance soil properties (Box 12.2). (3) **Commercial composting** systems (see Section 12.10) represent a low-energy use, low-cost way to produce an easy-to-handle, nonodiferous, relatively high-analysis, slow-release fertilizer. Composting of manure at large cattle feedlots (Figure 16.25, *left*) is one way of reducing leaching and runoff losses of soluble nutrients and reducing the volume of manure that must be transported. (4) **Anaerobic digestion** (discussed previously) can be enhanced with the collection of biogas, which contains about 80% methane and 20% carbon dioxide and can be burned much like commercial natural gas. Small-scale manure digesters can supply cooking and heating fuel for remote villages and large-scale digesters can generate electricity to power modern farms.

Methods of Manure Application

Similar to the impacts of manure handling, how farmers apply manure to their fields can have a large impact on the efficiency of nutrient use and the level of losses by surface runoff, volatilization, and leaching. Since farm animals produce manure every single day, manure handling is a constant daily process and farmers naturally tend to seek the quickest, most convenient methods of dealing with its management. The convenient thing, especially for the collect-and-spread-daily management approach, is to apply the manure to the nearest fields in all kinds of weather. Such fields will often carry a legacy of nutrient-saturated soils and continue to leak nitrogen and phosphorus into waterways for many years after this outdated practice is ceased. Another very detrimental practice is the application of manure to frozen soils in cold climates. Although convenient because the frozen soil will support heavy manure wagons without causing them to bog down in mud, the manure nutrients cannot soak into the soil and will wash off the surface with snowmelt in spring.

The advent of large diameter drag hoses or dragline systems of manure-spreading technology has allowed more flexibility in manure application times as this method eliminates the need for driving extremely heavy tank-wagons (Figure 16.26*c*,*d*) of liquid manure across the field. In the dragline systems, liquid manure is pumped from a lagoon or large tank at the edge of a field through a long, flexible 12–15 cm diameter hose to manure application implements pulled across the field by a tractor.

The various handling and storage methods discussed in the previous section can allow farmers to wait for the optimal time for applying manure, when the manure can be incorporated into

Figure 16.25 *Contrasting methods of storing and handling manure.* (Left) *A water truck maintains moist conditions in a long compost windrow located in an Arizona cattle feedlot in the United States. Note the mixture of materials in the windrows, including dark, low-C/N manure and lighter, high-C/N straw. The windrow will be turned once or twice to stimulate decomposition. The finished compost will be easy-to-handle and take up about half the volume of the original manure.* (Right) *Liquid manure is being pumped out of a lined anaerobic storage lagoon into tractor-drawn manure wagons used to spray the manure onto crop fields on this dairy farm in the eastern USA.*
[Photos courtesy of Dr. Mohammed A. Zerkoune, University of Arizona (*left*) and Ray R. Weil (*right*)]

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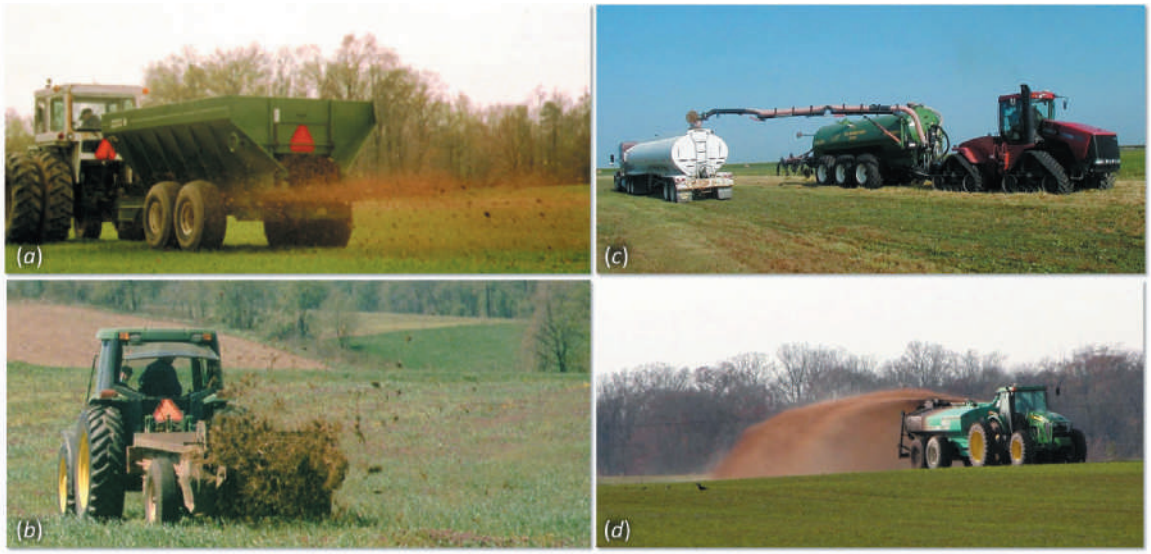

Figure 16.26 *Examples of manure-spreading methods. Solid manure from poultry (a) and cattle (b) is spread on the surface of crop- or pastureland. Liquid manure from hog (c) and dairy (d) farms can be either injected into the soil (c) or sprayed on the surface (d). Note the crawler tread tractor and multiwheeled manure wagon in (c) designed to minimize compaction of soil by the heavy load. The liquid manure is likely greater than 95–99% water while the solid manures may be only 50–90% water.* (Photo c courtesy of J. Gruver, Western Illinois University; others courtesy of Ray R. Weil)

the soil to avoid runoff losses and the nutrients can be immediately used by growing crops. Incorporation of manure into the soil by various tillage implements, however, can leave the soil surface exposed to erosion (see Section 17.5) and increase the loss of sediment and associated nutrients.

One solution is to inject the manure beneath the soil surface using a no-till implement with knife-like tines and rollers to leave the soil surface and residue cover almost undisturbed. Such soil injection has been widely practiced for liquid manure, but equipment that can inject solid dry manure, such as pelleted poultry house litter, is still under development. Compared to that broadcast on the soil surface, manure injected by such equipment loses far less nitrogen by ammonia volatilization and phosphorus by surface runoff (Figure 16.27).

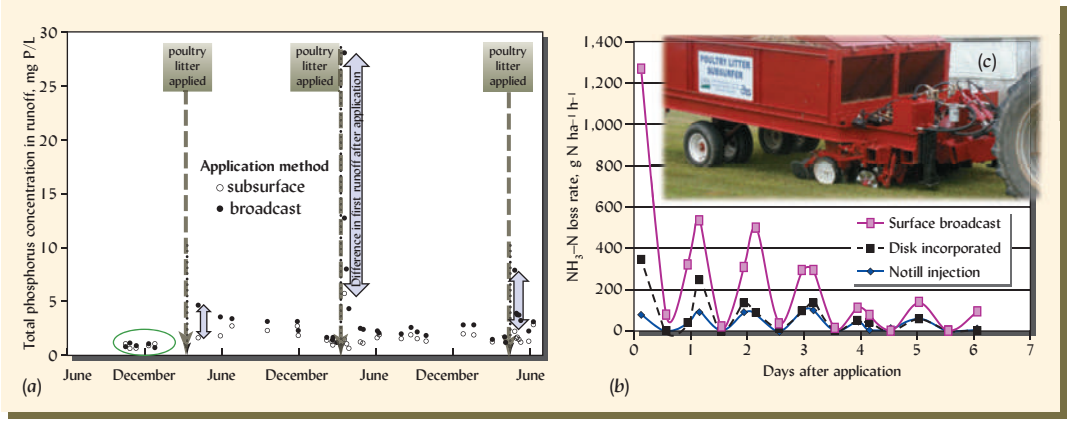

Figure 16.27 *No-till injection of dry poultry manure greatly reduces nutrient losses as compared to broadcast application. (a) Phosphorus concentrations in surface runoff from pasture watersheds treated with poultry manure applied by surface broadcasting or by subsurface injection. Runoff P was equally low from both side-by-side watersheds before any poultry manure was applied (green circle at left). Most of the P losses occurred with the first runoff-producing rain after each manure application (thick blue vertical arrows indicate the large difference in P concentration between application methods). (b) Nitrogen loss to the atmosphere as ammonia gas occurred mainly during the first few days (but not nights) after application. The ammonia loss was also much greater when manure was broadcast than when it was incorporated by disk tillage (22% as much loss) or by no-till injection (12% as much loss). (c) The photo shows an experimental manure applicator being developed by US Department of Agriculture researchers to inject dry poultry manure into the soil without disturbing the soil residue cover.* [Redrawn from Pote et al. (2011) and Pote and Meisinger (2014); (c) USDA/ARS]

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Increased adaption of such technologies, along with more closely integrated animal and crop farming systems, could help to redress the serious nutrient imbalances and pollution associated with manure production in industrialized agriculture.

16.5 INDUSTRIAL AND MUNICIPAL BY-PRODUCTS[6]

In addition to farm manures, four major types of organic wastes are of significance in land application: (1) municipal garbage, (2) sewage effluents and sludges (see Sections 16.6 and 18.7), (3) food-processing wastes, and (4) wood wastes of the lumber industry. Because of their uncertain content of toxic chemicals, these and other industrial wastes may or may not be suitable application to soils.

Society's concern for environmental quality has forced waste generators to seek nonpolluting, but still affordable, ways of disposing of these materials. Although once seen as mere waste products to be flushed into rivers and out to sea, some of these materials are increasingly seen as sources of nutrients and organic matter that can be used beneficially to promote soil productivity in agriculture, forestry, landscaping, and disturbed-land reclamation.

Garbage

Household and municipal garbage has been used for centuries by traditional societies to enhance soil fertility. In industrial countries most municipal solid waste (MSW) is incinerated or landfilled (see Section 18.10), but growing concerns about air quality, scarcity of landfill space, and greenhouse gas emissions are raising the level of interest in using soil application as a means of MSW disposal. About 50–60% of MSW consists of decomposable organic materials (paper, food scraps, yard waste, street tree leaves, etc.). Once the inorganic glass, metals, and so forth are removed, MSW can be ***composted*** (Section 12.10). Because MSW contains so much low nitrogen paper and cardboard, combining MSW with more nutrient-rich materials such as sewage sludge or animal manure greatly improves the composting process and the quality of the MSW compost that is then applied to the land. Even such mixed MSW compost is low enough in nutrient concentrations (see Table 16.9) that it is an expensive way to distribute nutrients. However, alternative disposal options are often even more expensive. One advantage of composting MSW is the reduced production of greenhouse gases as compared to allowing the materials to decompose in anaerobic landfills or manure lagoons. Potentially, the entire annual production of organic-material MSW, some 80 million cubic meters in the United States, could be recycled as a soil amendment using less than 10% of the agricultural land in the country. Increasing numbers of compost operations of all sizes are being run by communities, small businesses, or even individuals. Still, the environmental impacts of transporting (usually by diesel truck) large amounts of low nutrient material over long distance must be considered.

Food-Processing Wastes

Land application of food-processing wastes is being practiced in selected locations, but the practice is focused more on pollution abatement than on soil enhancement. Liquid wastes are commonly applied through sprinkle irrigation to permanently grassed fields. Kitchen food wastes, on the other hand, lend themselves to effective composting, whether at the scale of an individual household or a large institution such as is practiced by several major universities.

Wood Wastes

Sawdust, wood chips, and shredded bark from the lumber industry have long been sources of soil amendments and mulches, especially for home gardeners and landscapers. Because of their high C/N ratios and high lignin contents, these materials decompose very slowly. They make good mulching material, but do not readily supply plant nutrients. In fact, sawdust incorporated into soils to improve soil physical properties may cause plants to become nitrogen deficient unless an additional source of nitrogen is applied (see Section 12.3).

[6]For a collection of technical papers discussing the potential benefits and problems associated with the land application of these by-products, see Powers and Dick (2000).

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Wastewater Treatment By-Products

For nearly two centuries, since the development of piped drinking water, flush toilets, and sewage systems, urban inhabitants have created vast quantities of sewage by using clean water as a vehicle to carry away human wastes. Although the typical system is fundamentally wasteful of water, energy, organic matter, and nutrients, at least sewage treatment has evolved to help society avoid polluting rivers and oceans with the pathogens, oxygen-demanding organic debris, and eutrophication-causing nutrients in sewage. In most advanced countries, sewage is given both primary and secondary treatment—and often advanced tertiary treatment—before the water is discharged back into a stream or river (Figure 16.28). The ever-more-stringent effort to clean up wastewater before returning it to natural waters has two basic consequences. First, the amount of material *removed* from the wastewater during the treatment process has increased tremendously. This solid material, known as sewage ***sludge***, must also be disposed of safely. Second, a goal of advanced wastewater treatment is to remove nutrients (mainly phosphorus, but increasingly also nitrogen) from the treated water that is returned to rivers—the liquid known as sewage **effluent**. The final stages of effluent clean up can be accomplished safely and economically by allowing the partially treated effluent to interact with a soil–plant system. Therefore, soils can assist with the sewage problem in two ways: (1) as a system of assimilating, recycling, or disposing of the solid sludge; and (2) as a means of carrying out the final removal of nutrients and organics from the liquid effluent.

Sewage Effluent

Some cities operate sewage farms on which they produce crops, usually animal feeds and forages, the sale of which can offset part of the expense of effluent disposal. Forest irrigation is another cost-effective method of final effluent cleanup and produces enhanced tree growth as a bonus (Figure 16.29, *left*). The rate of wood production is greatly increased as a result of both the additional water and the additional nutrients supplied therewith. This method of advanced wastewater treatment is used by a number of cities around the world.

In a carefully planned and managed effluent irrigation system, the combination of: (1) nutrient uptake by the plants, (2) adsorption of inorganic and organic constituents by soil colloids,

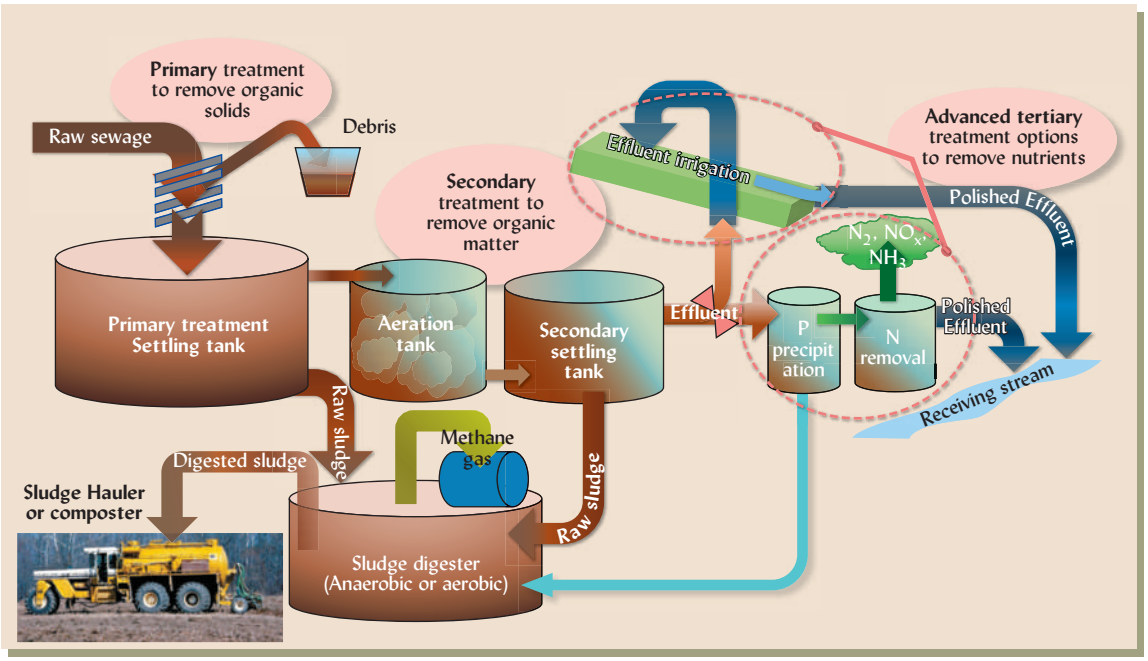

Figure 16.28 *Modern sewage treatment, which effectively cleans urban wastewater, produces two primary products: the solids removed from the wastewater, a material known as sewage sludge, and the partially cleaned up water that leaves the treatment plant, known as sewage effluent. Both products can be beneficially applied to soils if the process is properly planned and controlled.* (Diagram and photo courtesy of Ray R. Weil)

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Figure 16.29 *Carefully managed application to soils has the potential to safely dispose of and beneficially use both the liquid (effluent) and solid (sludge) products of wastewater treatment. The soil–plant system may benefit from the contained water, nutrients, and organic carbon. However, a system's approach must be instituted to avoid unwanted and potentially dangerous constituents. The photos illustrate* (left) *irrigating with effluent in a pine plantation and* (right) *injecting sewage sludge into cropland soil.* (Photos courtesy of Ray R. Weil)

and (3) degradation of organic compounds by soil microorganisms results in the purification of the wastewater. Percolation of the purified water eventually replenishes the groundwater supply.

Sewage Sludge or Biosolids

Sewage sludge is the solid by-product of domestic and/or industrial wastewater treatment plants (Figure 16.28). It has been spread on the land for decades (Figure 16.29, *right*), and its use will likely increase in the future. If sewage sludge has been treated to meet certain standards of low pathogen and contaminant levels, the term **biosolids** may be applied. The product Milorganite®, a dried, activated (oxygenated) sludge sold by the City of Milwaukee Sewerage Commission, has been widely used as a slow-release fertilizer in North America since 1927, especially on turfgrass. Numerous other cities market composted sludge products to landscapers and other specialty users. However, the great bulk of sewage sludge used on land is applied as liquid slurry or as partially dried cake.

Composition of Sewage Sludge. As might be expected, the composition of sludge varies from one sewage treatment plant to another. The variations depend on the nature of treatment the sewage receives, especially the degree to which the organic material is allowed to digest. Representative values for plant nutrients are given in Table 16.9. Like manure and other organic nutrient sources, sewage sludge contributes micronutrients as well as macronutrients. Levels of plant micronutrient metals (zinc, copper, iron, manganese, and nickel) as well as other heavy metals (cadmium, chromium, lead, etc.) are determined largely by the degree to which industrial wastes have been mixed in with domestic wastes. In the United States, the levels of metals and industrial chemicals in sewage are far lower than they were in the past, because of source-reduction programs that require industrial facilities to remove pollutants *before* sending their sewage to municipal treatment plants (see Section 18.7). As with livestock manures, pharmaceuticals and natural or artificial hormones are also of concern in human wastes. Vigilance must be maintained to avoid sludges too contaminated for safe land application.

In comparison with inorganic fertilizers, sludges are generally low in nutrients, especially potassium (which is soluble and found mainly in the effluent). Representative levels of N, P, and K are 4, 2, and 0.3%, respectively (see Table 16.9). The phosphorus content is higher where advanced sewage treatment is designed to remove phosphorus from the effluent and deposit it in the sludge (see Box 14.2). However, if the sewage treatment precipitates phosphorus by reactions with iron or aluminum compounds, the phosphorus in the sludge will likely have a very low availability to plants.

Integrated Recycling of Wastes

For most of the industrialized countries, widespread recycling of organic wastes other than animal manures is a relatively recent phenomenon. In heavily populated areas of Asia, however, and particularly in China and Japan, complex integrated recycling was practiced long ago (Figure 16.30). There, organic "wastes" were traditionally used for biogas production, as food for fish, and as a source of heat from compost piles. The plant nutrients and organic matter were recycled and returned to the soil. Despite China's increasing use of chemical fertilizers, the traditional respect for what others might see as wastes supports such complex recycling systems that continue to supply a significant proportion of the nutrients used in China's

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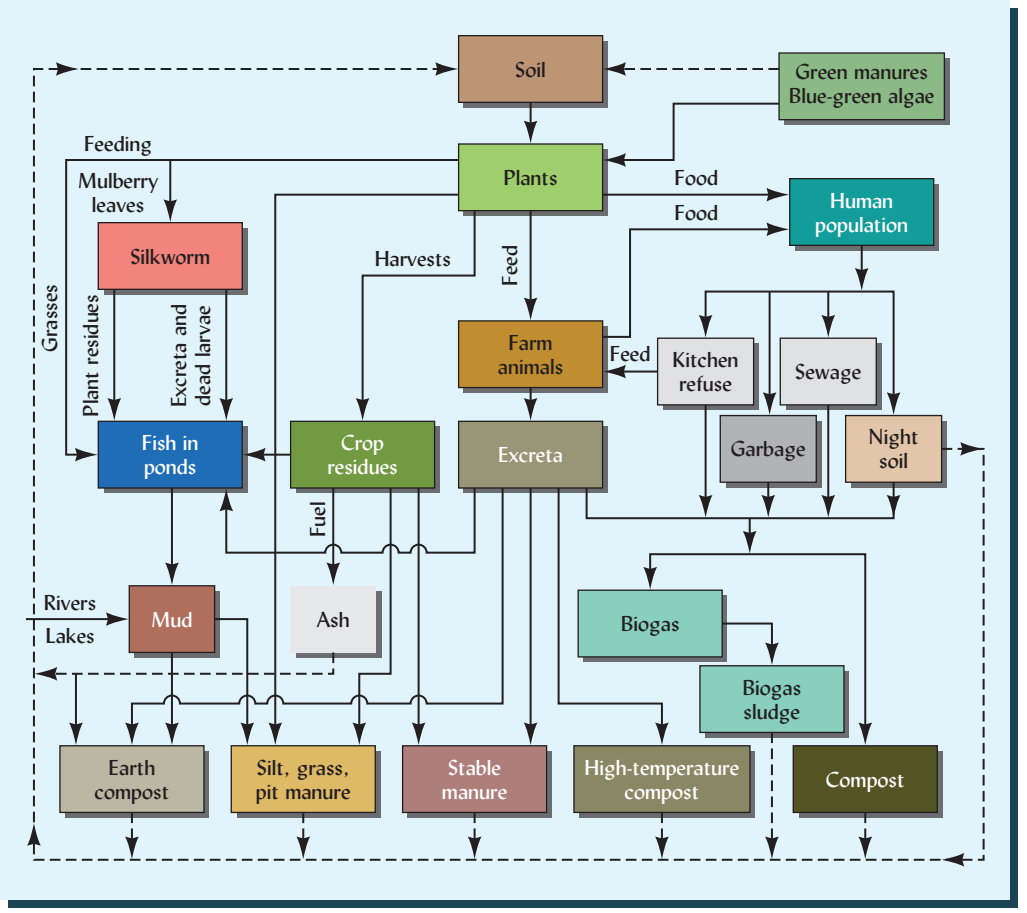

Figure 16.30 *Traditional recycling of organic wastes and nutrient elements as once commonly practiced in China. Note the degree to which the soil is involved in the recycling processes. (Concepts from FAO (1977) and Yang (2006).)* (Photos courtesy of Ray R. Weil)

agriculture. As they look to achieve a more sustainable future, Western countries have much to learn from traditional Chinese attitudes and practices.

16.6 PRACTICAL UTILIZATION OF ORGANIC NUTRIENT SOURCES[7]

In Section 12.5 we discussed the many beneficial effects on soil physical and chemical properties that can result from amendment of soils with decomposable organic materials. Here we will focus on the principles of efficient and ecologically sound management of nutrients from plant residues, sewage sludge, farm manure, MSW compost, and other organic materials.

Undoubtedly, the largest pool of organic material available to be applied to soils is the residue of plants grown on the land. Farmers are increasingly interested in using **cover crops** to produce additional nutrient-rich plant residues and to assist them in managing nutrients for their cash crops. The concept of cover crops—plants grown for soil improvement rather than for sale—was previously introduced along with the idea of using them to capture and recycle nutrients that might otherwise leach away (Section 16.2), as was the use of legume cover crops to enrich soils with nitrogen fixed from the atmosphere (Section 13.15). Cover crops may be most beneficial if nutrient release from their residues is timed to be in synchrony with the nutrient uptake needs of the following main crop. This synchrony can be achieved with careful management

[7]For an example of special, high rate applications of organic wastes that beg some interesting nutrient management questions, see research on a scheme to reduce greenhouse gas emissions from California agriculture while increasing the productivity and soil organic matter content of California's semiarid grasslands by making a single very large application of composted organic waste (Ryals and Silver, 2013; Wick and Creque, 2014).

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of such factors as the composition of the cover crop residues and the physical contact between these residues and the soil. One way to manage cover crop nutrient composition is to carefully select the species or mixture of species grown. For example, low C/N ratio legume species may be mixed with high C/N ratio grass species in different proportions to achieve faster or slower decomposition and the release or immobilization of nitrogen, as may be desired. The rates of decomposition and nutrient cycling can also be hastened by tillage that chops the residues into small pieces and mixes them in with moist soil. Using no-till techniques to terminate cover crops will have the opposite effect, spreading the nutrient release more evenly over the season and preserving a weed-suppressing, water-conserving surface mulch (Figure 16.31).

When using organic nutrient resources, usually the first step (required by law in some cases) is to have a representative sample analyzed for nutrient contents and other qualities by a reputable laboratory. The rate of application is generally governed by the amount of nitrogen or phosphorus that the organic material will make available to plants.

Nitrogen usually is the first criterion because it is needed in the largest quantity by most plants, and because nitrogen can present a pollution problem if applied in excess (see Section 13.8). The ratio of P/N in most animal-derived organic sources is much higher than in plant tissue. Consequently, if organic materials supply sufficient N to meet plant needs, they probably supply excessive levels of P (see Section 14.2); the buildup of soil P must be taken into account in the long run. For soils already high in available P, the application rate for an organic amendment may be limited by the P, rather than by the N content. Potentially, toxic heavy metals in some materials may also limit the rate of application (see Section 18.7).

A small fraction of the N in manure or sludge may be soluble (ammonium or nitrate) and immediately available, but the bulk of the N must be released by microbial mineralization of

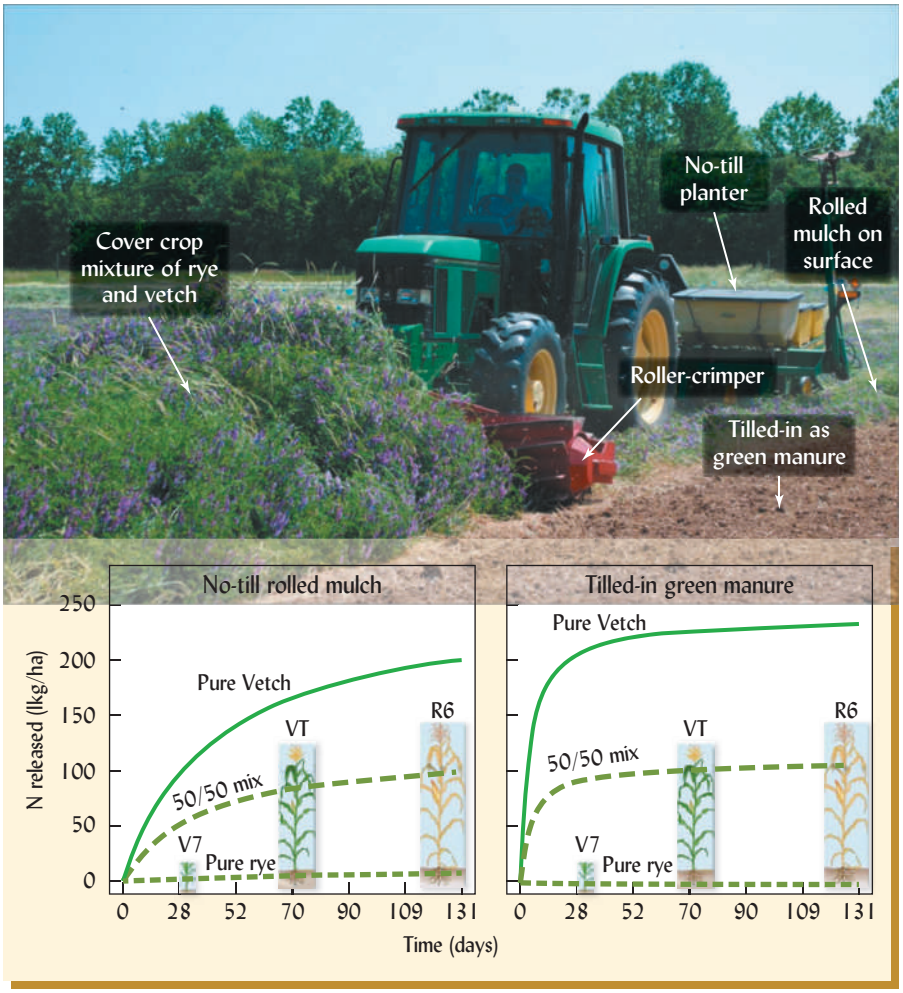

Figure 16.31 *Farmers are increasingly interested in using cover crops to assist with nutrient management. Here a mixed cover crop of vetch and rye is terminated with a roller-crimper and a corn crop is planted into the residue with a no-till planter. Nutrient release from cover crop residues in synchrony with the nutrient needs of the following main crop depends largely on the composition of the cover crop and how it is physically handled. Composition can be managed by mixing different proportions of high N legumes (e.g., vetch) with lower N grasses (e.g., rye). The rate of release is faster if the cover crop is tilled into the soil, and is more evenly spread out over the season if the cover crop is applied as surface mulch.* [Data and concepts from Poffenbarger et al. (2015). Photo courtesy of Marose, Betty H]

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organic compounds. Table 16.11 estimates N mineralization rates for various organic materials. Materials partially decomposed during treatment and handling (e.g., by composting or digestion) release a lower percentage of their nitrogen. For example, Figure 16.32 compares the rate of nitrate-N released from fresh and composted poultry litter.

If a field is treated annually with an organic material, the application rate needed will become progressively smaller because, after the first year, the amount of nitrogen released from material applied in previous years must be subtracted from the total to be applied afresh (see Box 16.2). This is especially true for composts for which the initial availability of the nitrogen is quite low. Instead of making progressively smaller applications, another practical strategy is to use a moderate application every year, but supplement the nitrogen from other sources in the first few years until nitrogen release from previous and current applications can supply the entire requirement (see also Section 16.4).

Table 16.11
RELEASE OF MINERAL NITROGEN FROM VARIOUS ORGANIC MATERIALS APPLIED TO SOILS, AS PERCENT OF THE ORGANIC NITROGEN ORIGINALLY PRESENT[a]

For example, if 10 Mg of poultry floor litter initially contains 300 kg N in organic forms, 50% or 150 kg of N would be mineralized in year 1. Another 15% (0.15 × 300) or 45 kg of N would be released in the year 2.

Organic nitrogen source	Year 1	Year 2	Year 3	Year 4
Poultry floor litter	55	20	8	3
Dairy manure (fresh solid)	25	18	9	4
Swine manure lagoon liquid	45	12	6	2
Feedlot cattle manure	30	15	6	2
Composted feedlot manure	18	18	4	1
Lime-stabilized, aerobically digested sewage sludge	40	12	5	2
Anaerobically digested sewage sludge	20	8	4	1
Composted sewage sludge	10	5	3	2
Activated, unstabilized sewage sludge	45	15	4	2
Flowering stage legume cover crop foliage	80	15	5	2

[a]These values are approximate and may need to be increased for warm climates or sandy soils and decreased for cold or dry climates or heavy clay soils. Release rates estimated from many sources.

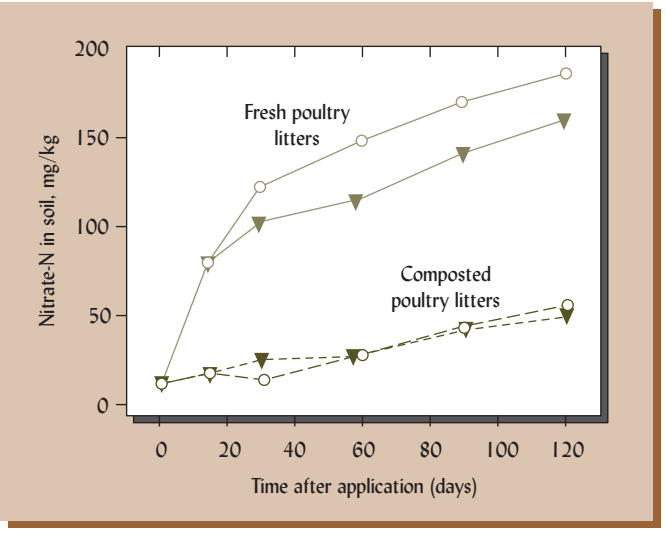

Figure 16.32 *Organic material stabilized by digestion or composting mineralizes more slowly than the raw unstabilized material. Here, nitrate nitrogen accumulates in a silt loam soil incubated with composted or fresh poultry litter from two sources. Amounts each of the litters sufficient to provide 230 mg of total N per kg of dry soil were incubated with moist soil at 25 °C for 120 days.* [Modified from Preusch et al. (2002)]

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BOX 16.2

CALCULATION OF AMOUNT OF ORGANIC NUTRIENT SOURCE NEEDED TO SUPPLY A DESIRED AMOUNT OF NITROGEN

If the soil phosphorus level is not already above the optimal range, the rate of release of available nitrogen usually determines the proper amount of manure, sludge, or other organic nutrient source to apply. The amount of nitrogen made available in any year should meet, but not exceed, the amount of nitrogen that plants can use for optimum growth. Our example here is a field producing corn two years in a row. The goal is to produce 7000 kg/ha of grain each year. For this field, this yield normally requires the application of 120 kg/ha of available nitrogen (about 58 kg of grain per kg N applied; see Section 16.13). We expect to obtain this N from a lime-stabilized sewage sludge containing 4.5% total N and 0.2% mineral N (ammonium and nitrate).

Year 1
Calculation of amount of sludge to apply per hectare:

% organic N in sludge = total N − mineral N = 4.5% − 0.2% = 4.3%.
Organic N in 1 Mg of sludge = 0.043 × 1000 kg = 43 kg N.
Mineral N in 1 Mg of sludge = 0.002 × 1000 kg = 2 kg N.

Mineralization rate for lime-stabilized sludge in first year (Table 16.11) = 40% of organic N.

Available N mineralized from 1 Mg sludge in first year
= 0.40 × 43 kg N = 17.2 kg N.

Total available N from 1 Mg sludge
= mineral N + mineralized N = 2.0 + 17.2 = 19.2 kg N.

Amount of (dry) sludge needed
= 120 kg N/(19.2 kg available N/Mg dry sludge)
= 6.25 Mg dry sludge.

Adjust for moisture content of sludge (e.g., assume sludge has 25% solids and 75% water).

Amount of wet sludge to apply:
6.25 Mg dry sludge/(0.25 Mg dry sludge/Mg wet sludge)
= 6.25/0.25 = 25 Mg wet sludge.

Year 2
Calculate amount of N mineralized in year 2 from sludge applied in year 1:

Second year mineralization rate (Table 16.11)
= 12% of original organic N.

N mineralized from sludge in year 2
= 0.12 × 43 Kg N/Mg × 6.25 Mg dry sludge
= 32.25 kg N from sludge in year 2.

Calculate amount of sludge to apply in year 2:

N needed from sludge applied in year 2
= N needed by corn
− N released from sludge applied in year 1
= 120 kg – 32.25 kg = 87.75 kg N needed/ha.

Amount of (dry) sludge needed per ha
= 87.75 kg N/(19.2 kg available N/Mg dry sludge)
= 87.75/19.2 = 4.57 Mg dry sludge/ha.

Adjust for moisture content of sludge (e.g., assume sludge has 25% solids and 75% water).

Mg of wet sludge to apply:
4.57 Mg dry sludge/(0.25 Mg dry sludge/Mg wet sludge)
= 4.57/0.25 = 18.3 Mg wet sludge.

Note that the 10.82 Mg dry sludge (6.25 + 4.57) also provided plenty of P: 216 kg P/ha (assuming 2% P; see Table 16.9), an amount that greatly exceeds the crop requirement and will soon lead to excessive buildup of P.

Heavy One-Time Applications for Special Uses

The organic matter component plays a dominant role in applications of organic nutrient sources to soil areas denuded by erosion or severe human disturbance (Table 16.12). Improvements in water-holding capacity and soil structure brought about by decomposing organic materials may be just as important as the nutrient-supplying capacity of the amendment. For example, in the mine reclamation project featured in Table 16.12, the researchers noted that in addition to the effects shown, woody and herbaceous native perennial plants preferentially invaded the sludge-treated plots.

In a different project in central California, USA (http://www.marincarbonproject.org/), researchers treated test plots of low productivity semiarid rangeland with about 140 Mg/ha of compost made from dairy manure and suburban yard wastes. This one-time application covered the land to about 1.3 cm depth and supplied approximately 70,000 kg/ha dry organic matter containing 1300 kg/ha nitrogen and probably at least half that much phosphorus. Not surprisingly, the combination of nutrients, carbon and moisture retaining mulch from this single heavy application of compost had a long-lasting positive effect on rangeland productivity

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Table 16.12
HEAVY APPLICATION OF SEWAGE SLUDGE HELPS RESTORATION OF DRASTICALLY DISTURBED SITE[a]
The revegetation effort benefited from both the nutrients and the organic matter in the sludge. Compared to fertilizer, sludge application increased the concentration of some potentially toxic metals in grass tissue, but not above normal levels. In the case of nickel, tissue levels were actually reduced because plant growth increased more than plant nickel uptake.

	Standing plant biomass		Metals in plant tissue in year 2, mg/kg		
	Year 2	Year 5	Cr	Ni	Cu
Control (no amendment)	1.55	1.49	0.9	5.7	12.1
Commercial fertilizer	4.79	3.10	0.5	1.6	14.8
Sewage sludge (368 Mg/ha)	5.68	3.07	1.8	0.6	24.8

[a]The sludge was compared to fertilizer or no amendment. Acid, infertile, shaley soils forming from coal mine spoil were seeded in year 1 with a mix of grass and broadleaf species.
Data selected from Haering et al. (2000).

and soil organic matter. However, nitrogen leaching and phosphorus in runoff were not reported. Such examples suggest that on degraded or low productivity land, initial applications of 50 to more than 100 Mg/ha may be justified to supply organic matter, mulch, and nutrients, provided the material is not so high in nitrogen or phosphorus as to create the potential for nutrient pollution by leaching or runoff.

16.7 INORGANIC COMMERCIAL FERTILIZERS

The worldwide agricultural use of fertilizers increased dramatically after the mid-20th century (Figure 16.33), accounting for a significant part of the equally dramatic increases in crop yields during the same period. Improved soil fertility through the application of fertilizer nutrients is an essential factor in enabling the world to feed the billions of people that are being added to its population (see Section 20.4). Most of the increase has been in the use of nitrogen, which has increased its share of the total N, P, and K applied from 50% in 1960 to over 70% in recent years.

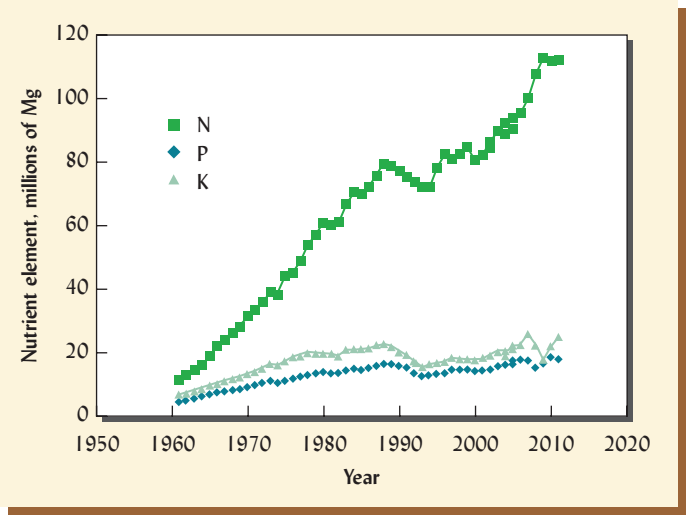

Figure 16.33 *World fertilizer use since 1960 by major nutrient element. The use of nitrogen (N) has increased much faster than that of phosphorus (P) and potassium (K). The dip in world fertilizer use in the early 1990s was due mainly to drastic reductions in Russia and Ukraine after the collapse of the Soviet Union. In most industrialized countries fertilizer use has leveled off or declined, but it continues to increase in China and India, and in much of the developing world. In much of Africa, the removal of nutrients in crop harvests still exceeds the amounts returned to the soil.* [Data selected from FAOSTAT (FAO, 2014)]

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Fertilizer use has also increased in forestry. The need to supplement forest soil fertility is increasing as the demands for forest products increase the removal of nutrients and competing uses of land leave forestry with more infertile, marginal sites. Currently, most fertilization in forestry is concentrated on tree nurseries and on seed trees, where the benefits of fertilization are relatively short term and of high value, and the logistics of fertilizer application are not so difficult and expensive as for extensive forest stands. However, fertilization of new forest plantings and existing stands is increasingly practiced in Japan, Canada, the Scandinavian countries, Australia, and northwestern and southeastern United States, with the fertilizer spread by helicopter. Nearly all the fertilizer used in forestry has been to supply nitrogen, but in recent decades applications of phosphorus to forest have become more common.

Regional Use of Fertilizers

To tell whether fertilizers are contributing to soil quality enhancement or to environmental degradation one must consider more localized regional use statistics. For example, in Europe and East Asia where moisture is abundant and intensified cropping is common, fertilizer nutrient application rates are nearly triple the world average. In the Netherlands, nitrogen additions from fertilizers and manures have been more than three times the removal of this element in harvested crops. In contrast, the nutrient supply in sub-Saharan Africa soils is literally being mined—far less is added from all sources than is removed in the crops. The fertilizer nutrient rate in this region is only about 10% of the world average. Thus, site-specific information is needed to evaluate the role of fertilizers in meeting humanitarian and environmental goals.

Origin and Processing of Inorganic Fertilizers

Most fertilizers are inorganic salts containing readily soluble plant nutrient elements. Nitrogen fertilizers are manufactured using natural gas and the elemental N_2 gas in air under very high temperatures and pressures to synthesize ammonia gas, NH_3. This industrial fixation is termed the Haber process and consumes tremendous quantities of energy—usually from fossil fuel. Therefore most nitrogen fertilizer factories are located near natural gas fields in Russia, China, India, Nigeria, and Texas, USA. The industrial process of nitrogen fixation has transformed the global nitrogen cycle (see Section 13.2).

Phosphorous fertilizers are processed by dissolving phosphate mineral (apatite) bearing rocks with sulfuric acid. Phosphate rock deposits are located around the world; but the vast majority of remaining known reserves are located in Morocco and to a lesser degree in China.

Most potassium fertilizers are simply purified from natural geological deposits of salts formed from the evaporation of ancient seawater. These underground deposits are found in many locations, including sites in Canada, France, Germany, and Russia, and New Mexico, USA.

When the manufactured ammonia gas is put under moderate pressure, it liquifies, forming anhydrous ammonia. Because of its low cost and ease of application, much nitrogen is applied directly to soils as anhydrous ammonia. This compound is also the starting point for the manufacture of most other nitrogen carriers, including urea, ammonium nitrate, ammonium sulfate, sodium nitrate, and aqueous nitrogen solutions.

Many commercial fertilizers contain two or more macronutrient nutrient elements. In some cases, mixtures of the primary nutrient carriers are blended together (Figure 16.34). But in fertilizers, a given compound may carry two nutrients, examples being diammonium phosphate, potassium sulfate, potassium nitrate, and ammonium sulfate. Care must be used in selecting the components of a mixed fertilizer since some compounds are not compatible with others, resulting in poor physical condition and reduced nutrient availability in the mixture.

Properties and Use of Inorganic Fertilizers

The composition of inorganic commercial fertilizers is much more precisely defined than is the case for the organic materials discussed in the previous sections. Table 16.13 lists the nutrient element contents and other properties of some of the more commonly used inorganic fertilizers. In most cases, fertilizers are used to supply plants with the macronutrients nitrogen, phosphorus, sulfur, and/or potassium. Fertilizers that supply magnesium, calcium, and the micronutrients are also manufactured.

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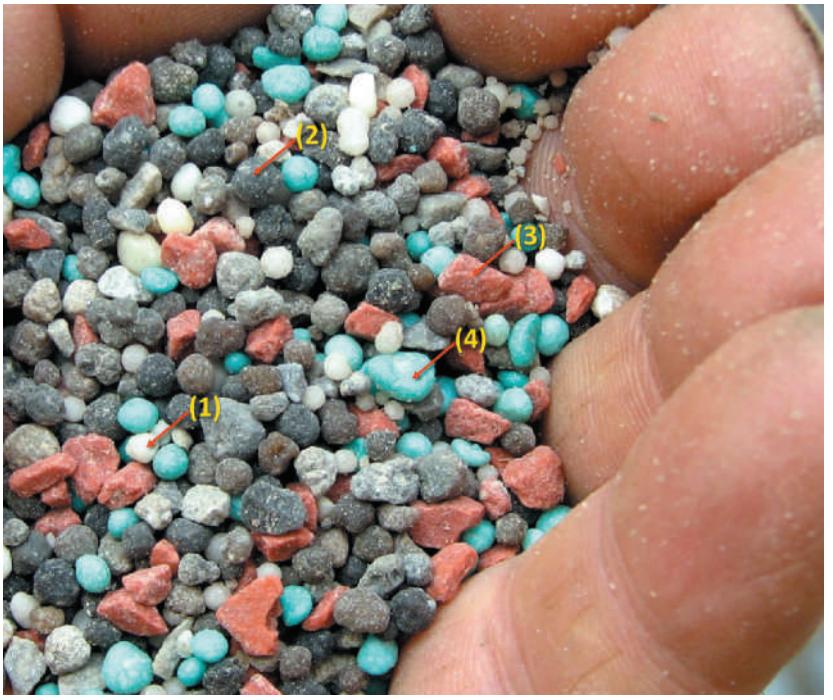

Figure 16.34 *A handful of a dry, granular fertilizer blend. Most primary fertilizer materials exhibit characteristic properties such as color, texture, particle size and shape. In the photo smooth, white pearl-like beads or prills of urea (1) are easily identified, as are the dark gray, rough granules of diammonium phosphate (2) and the pinkish or white crystals of potassium chloride (3). The green-blue particles are micronutrient mixtures colored by copper sulfate.* (Photos courtesy of Ray R. Weil)

It can be seen from the data in Table 16.13 that a particular nutrient (say, nitrogen) can be supplied by many different *carriers*, or fertilizer compounds. Decisions as to which fertilizers to use must take into account not only the nutrients they contain, but also a number of other characteristics of the individual carriers. Table 16.13 provides information about some of these characteristics, such as the salt hazard (see also Section 10.7), acid-forming tendency (see also Section 13.8), tendency to volatilize, ease of solubility, and content of nutrients other than the principal one. Of the nitrogen carriers, anhydrous ammonia, nitrogen solutions, and urea are the most widely used. Diammonium phosphate and potassium chloride supply the bulk of the phosphorus and potassium used.

Physical Forms of Marketed Fertilizer

Commercial fertilizers in many countries are still sold in bags, transported to the field in trucks, then emptied by hand into fertilizer spreaders and applied to the land. However, less than 10% of all fertilizer in the United States is handled in this manner. Increases in fertilizer use rates and labor costs, along with improved means of transporting and handling the fertilizer and increased availability of custom applicators, have favored two alternative means of marketing fertilizer: (1) unbagged, dry solids handled in *bulk* form, and (2) *liquid* or fluid forms stored, transported, and applied from tanks. In both cases the costs, particularly in terms of labor, are reduced.

Bulk spreading, often done at times when trucks or large fertilizer spreaders can get on the land, is the favorite for applying multinutrient fertilizers. Liquid fertilizers comprise more than half of the single-nutrient carriers sold in the United States and about 40% of all fertilizers. Labor costs are low, since the fertilizer is transferred from one tank to another and applied to the field with the aid of mechanical—often computer-controlled pumps.

Fertilizer Grade

Commercial fertilizers were first manufactured in the late 19th and early 20th centuries. Analytical procedures and laws passed to regulate the new industry resulted in certain labeling and marketing conventions that are still in common use today.

Of these conventions it is most important to be familiar with the *fertilizer grade.* Every fertilizer label states the **grade** as a three-number code, such as 10-5-10 or 6-24-24. These

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Table 16.13
COMMONLY USED INORGANIC FERTILIZER MATERIALS: THEIR NUTRIENT CONTENTS AND OTHER CHARACTERISTICS

Fertilizer	Percent by weight N	P	K	S	Salt hazard	Acid formation[a]	Other nutrients & comments
Primarily sources of nitrogen							
Anhydrous ammonia (NH_3)	82				Low	−148	Pressurized equipment needed; toxic gas; must be injected into soil.
Urea [$CO(NH_2)_2$]	45				Moderate	−84	Soluble; hydrolyses to ammonium forms. Volatilizes if left on soil surface.
Ammonium nitrate (NH_4NO_3)	33				High	−59	Absorbs moisture from air; can be left on soil surface. Can explode if mixed with organic dust or S.
Sulfur-coated urea	30–40			13–16	Low	−110	Variable slow rate of release.
UF (ureaform-aldehyde)	30–40				Very low	−68	Slowly soluble; faster with warm temperatures.
UAN solution	30				Moderate	−52	Most commonly used liquid N.
IBDU (isobutylidene diurea)	30				Very low	—	Slowly soluble.
Ammonium sulfate [$(NH_4)_2SO_4$]	21			24	High	−110	Rapidly lowers soil pH; very easy to handle.
Sodium nitrate ($NaNO_3$)	16				Very high	+29	Hardens, disperses soil structure.
Potassium nitrate (KNO_3)	13		36	0.2	Very high	+26	Very rapid plant response.
Primarily sources of phosphorus							
Monoammonium phosphate ($NH_4H_2PO_4$)	11	21–23		1–2	Low	−65	Best as starter.
Diammonium phosphate [$(NH_4)_2HPO_4$]	18–21	20–23		0–1	Moderate	−70	Best as starter.
Triple superphosphate		19–22		1–3	Low	0	15% Ca.
Phosphate rock [$Ca_3(PO_4)_2 \cdot CaX$]		8–18[b]			Very low	Variable	Low to extremely low availability. Best as fine powder on acid soils. 30% Ca. Contains some Cd, F, etc.
Single superphosphate		7–9		11	Low	0	Nonburning, can place with seed. 20% Ca.
Bonemeal	1–3[b]	10[b]	0.4		Very low	—	Slow availability of N, P as for phosphate rock. 20% Ca.
Colloidal phosphate		8[b]			Very low	—	P availability as for phosphate rock. 20% Ca.
Primarily sources of potassium							
Potassium chloride (KCl)			50		High	0	47% Cl—may reduce some diseases.
Potassium sulfate (K_2SO_4)			42	17	Moderate	0	Use where Cl not desirable.
Wood ashes		0.5–1	1–4		Moderate to high	+40	About $^1/_2$ the liming value of limestone; caustic. 10–20% Ca, 2–5% Mg, 0.2% Fe, 0.8% Mn.
Greensand		0.6	6		Very low	0	Very low availability.
Granite dust			4		Very low	0	Very slow availability.
Primarily sources of other nutrients							
Basic slag		1–7			Low	+70	10% Fe, 2% Mn, slow availability; best on acid soils. 3–30% Ca, 3% Mg. Also use for its Si.
Gypsum ($CaSO_4 \cdot 2H_2O$)				19	Low	0	Stabilizes soil structure; no effect on pH; Ca and S readily available. 23% Ca.
Calcitic limestone ($CaCO_3$)					Very low	+95	Slow availability; raises pH. 36% Ca.
Dolomitic limestone [$CaMg(CO_3)_2$]					Very low	+95	Very slow availability; raises pH. ~24% Ca, ~12% Mg.
Epsom salts ($MgSO_4 \cdot 7H_2O$)				13	Moderate	0	No pH effect; water soluble; 2% Ca, 10% Mg.
Sulfur, flowers (S)				95	—	−300	Irritates eyes; very acidifying; slow acting; requires microbial oxidation.
Solubor					Moderate	—	Very soluble; compatible with foliar sprays. 20.5% B.
Borax ($Na_2B_4O_7 \cdot 10H_2O$)					Moderate	—	Very soluble. 11% B; 9% Na.
EDTA chelates					—	—	See label. Usually 13% Cu or 10% Fe or 12% Mn or 12% Zn.
Cu, Fe, Mn, or Zn sulfates				13–20			25% Cu, 19% Fe, 27% Mn, or 35% Zn, very soluble.

[a]A negative number indicates that acidity is produced; a positive number indicates that alkalinity is produced; kg $CaCO_3$/100 kg material needed to neutralize acidity.

[b]Highly variable contents.

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numbers stand for percentages indicating the *total* nitrogen (N) content, the *available* (citric acid soluble) phosphate (P_2O_5) content, and the *water soluble* potash (K_2O) content. Plants do not take up phosphorus and potassium as P_2O_5 or K_2O, nor do any fertilizers actually contain these chemical forms. The oxide expressions for phosphorus (P_2O_5) and potassium (K_2O) are relics of the days when geochemists reported the contents of rocks and minerals in terms of the oxides formed upon heating. Unfortunately, these expressions found their ways into laws governing the sale of fertilizers, and there is considerable resistance to changing them, although some progress is being made. In scientific work and in this textbook, the simple elemental contents are used (P and K) wherever possible. Box 16.3 and Figure 16.35 explain how to convert between the elemental and oxide forms of expression.

The grade is important from an economic standpoint because it conveys the analysis or concentrations of the nutrients in a carrier. When properly applied, most fertilizer carriers give equally good results for a given amount of nutrient element. The more concentrated carriers are usually the most economical to use, because less weight of fertilizer must be transported to supply the needed quantity of a given nutrient. Hence, economic comparisons among different equally suitable fertilizers should be based on the price per kilogram of nutrient, not the price per kilogram of fertilizer.

Fate of Fertilizer Nutrients

A common myth about fertilizers suggests that inorganic fertilizers applied to soil directly feed the plant, and that therefore the biological cycling of nutrients, such as described by Figures 13.2 for nitrogen and 14.8 for phosphorus, are of little consequence where inorganic

BOX 16.3

HOW MUCH NITROGEN, PHOSPHORUS, AND POTASSIUM IS IN A BAG OF 6-24-24?

Conventional labeling of fertilizer products reports percentage N, P_2O_5, and K_2O. Thus, a fertilizer package (Figure 16.35) labeled as 6-24-24 (6% nitrogen, 24% P_2O_5, 24% K_2O) actually contains 6% N, 10.5% P, and 19.9% K (see calculations below).

To determine the amount of fertilizer needed to supply the recommended amount of a given nutrient, first convert percent P_2O_5 and percent K_2O to percent P and K, by calculating the proportion of P_2O_5 that is P and the proportion of K_2O that is K. The following calculations may be used:

Given that the molecular weights of P, K, and O are 31, 39, and 16 g/mol, respectively:

$$\text{Molecular weight of } P_2O_5 = 2(31) + 5(16) = 142 \text{ g/mol}$$

$$\text{Proportion P in } P_2O_5 = \frac{2P}{P_2O_5} = \frac{2(31)}{2(31) + 5(16)} = 0.44$$

To convert $P_2O_5 \rightarrow$ P, multiply percent P_2O_5 by 0.44

$$\text{Molecular weight of } K_2O = 2(39) + 16 = 94$$

$$\text{Proportion K in } K_2O = \frac{2K}{K_2O} = \frac{2(39)}{2(39) + 16} = 0.83$$

To convert $K_2O \rightarrow$ K, multiply percent K_2O by 0.83

Thus, if the bag in Figure 16.35 contains 25 kg of the 6-24-24 fertilizer, it will supply 1.5 kg N (0.06 × 25); 2.6 kg P (0.24 × 0.44 × 25); and 5 kg K (0.24 × 0.83 × 25).

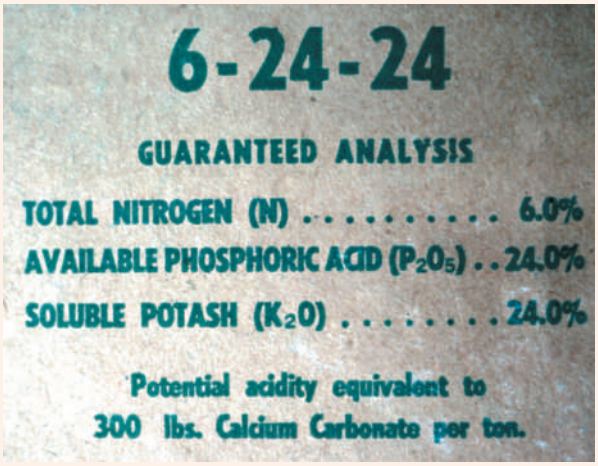

Figure 16.35 *A typical commercial fertilizer label. Note that a calculation must be performed to determine the percentage of the nutrient elements P and K in the fertilizer since the contents are expressed as if the nutrients were in the forms of P_2O_5 and K_2O. Also note that after interacting with the plant and soil, this material would cause an increase in soil acidity that could be neutralized by 300 units of $CaCO_3$ per 2000 units (1 ton = 2000 lbs) of fertilizer material.* (Photo courtesy of Ray R. Weil)

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fertilizers are used. The reality is that nutrients added by normal application of fertilizers, whether organic or inorganic, are incorporated into the complex soil nutrient cycles, and that relatively little of the fertilizer nutrient (from 10 to 60%) actually winds up in the plant being fertilized during the year of application. Even when the application of fertilizer greatly increases both plant growth and nutrient uptake, the fertilizer stimulates increased cycling of the nutrients, and the nutrient ions taken up by the plant come largely from various pools in the soil and not directly from the fertilizer. For example, some of the added N may go to satisfy the needs of microorganisms, preventing them from competing with plants for other pools of N. This knowledge has been obtained by careful analysis of dozens of nutrient studies that used fertilizer with isotopically tagged nutrients. Results from one such study are summarized in Table 16.14, which shows somewhat more N uptake from fertilizer than is typically reported. Generally, as fertilizer rates are increased, the efficiency of fertilizer nutrient use decreases, leaving behind in the soil an increasing proportion of the added nutrient.

The Concept of the Limiting Factor

Two German chemists (Justus von Liebig and Carl Sprengel) are credited with first publishing, in the mid-1800s, "the law of the minimum" which holds that *plant production can be no greater than that level allowed by the growth factor present in the lowest amount relative to the optimum amount for that factor.* This growth factor, be it temperature, nitrogen, sulfur, or water supply, will limit the amount of growth that can occur and is therefore called the ***limiting factor*** (Figure 16.36). This is similar to the adage that a chain is only as strong as its weakest link.

If a factor is not the limiting one, increasing it will do little or nothing to enhance plant growth. In fact, increasing the amount of a nonlimiting factor may actually reduce plant growth by throwing the system further out of balance. For example, if a plant is limited by lack of phosphorus, adding more nitrogen may only aggravate the phosphorus deficiency.

Looked at another way, applying available phosphorus (the first limiting nutrient in this example) may allow the plant to respond positively to a subsequent addition of nitrogen. Thus, the increased growth obtained by applying two nutrients together often is much greater than the sum of the growth increases obtained by applying each of the two nutrients individually. Such an *interaction* or *synergy* between two nutrients can be seen in the left panel of Figure 16.37, which also illustrates a physical limiting growth factor, soil compaction.

Table 16.14
SOURCE OF NITROGEN IN CORN PLANTS GROWN IN NORTH CAROLINA, USA, ON AN ENON SANDY LOAM SOIL (ULTIC HAPLUDALF) FERTILIZED WITH THREE RATES OF NITROGEN AS AMMONIUM NITRATE
The source of the nitrogen in the corn plant was determined by using fertilizer tagged with the isotope ^{15}N. Moderate fertilizer use increased the uptake of N already in the soil system as well as that derived from the fertilizer.

Fertilizer nitrogen applied, kg/ha	Corn grain yield, Mg/ha	Total N in corn plant, kg/ha	Fertilizer-derived N in corn, kg/ha	Soil-derived N in corn, kg/ha	Fertilizer-derived N in corn as percent of total N in corn	Fertilizer-derived N in corn as percent of N applied
50	3.9	85	28	60	33	56
100	4.6	146	55	91	38	55
200	5.5	157	86	71	55	43

Calculated from Reddy and Reddy (1993).

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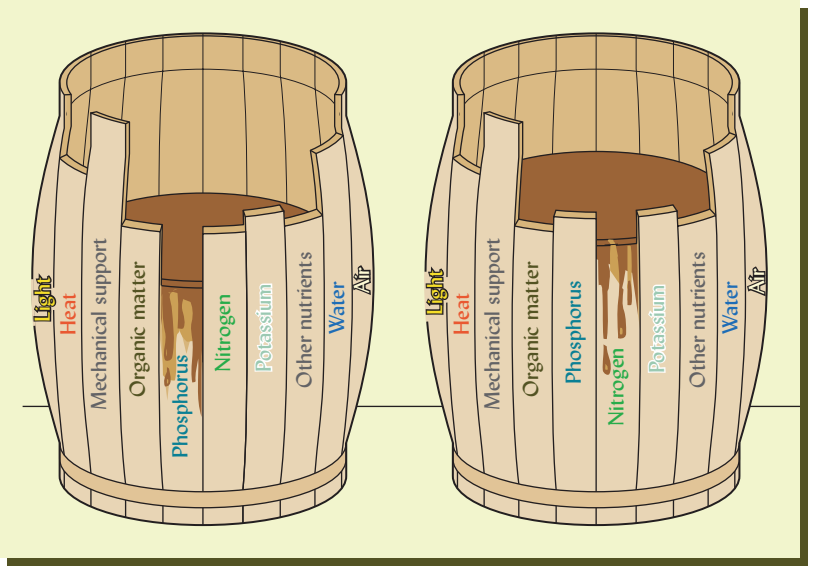

Figure 16.36 *An illustration of the law of the minimum and the concept of the limiting factor. Plant growth is constrained by the essential element (or other factor) that is most limiting. The level of liquid in the barrel represents the level of plant production. (Left) Phosphorus is represented as being the shortest barrel stave - the factor that is most limiting. Even though the other elements are present in more than adequate amounts, plant growth can be no greater than that allowed by the level of phosphorus available. (Right) When the phosphorus stave is lengthened (phosphorus is added), the level of plant production is raised until another factor becomes most limiting—in this case, nitrogen.*

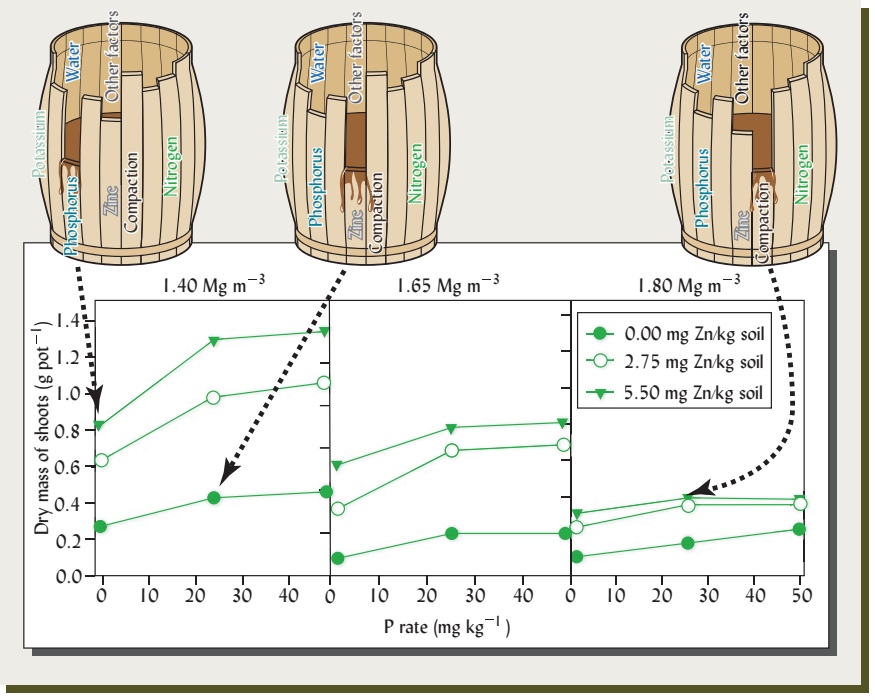

Figure 16.37 *The law of the minimum illustrated by responses of wheat to increasing levels of soil compaction (1.40, 1.65, and 1.80 Mg/m^3 bulk density), phosphorus fertilization (0, 25, and 50 mg P/kg soil) and zinc fertilization (0, 2.75, and 5.5 mg Zn/kg soil). The shortest (leaking) barrel stave shows which of these three factors is most limiting in various situations. For example, the middle barrel shows that zinc is most limiting when compaction is low and a moderate level of P has been applied—that is, there is a large response to adding zinc but little response to adding more P. This panel also illustrates a synergy or interaction between P and Zn—namely, the response to P is greater once some Zn is added, and vice versa. In the right panel compaction is limiting (bulk density = 1.8 Mg m^{-3}) and wheat shoots would respond to reduced compaction (compare to left panel) but not to adding more P or Zn.* [Graphs based on data in Barzegar et al. (2006)]

16.8 FERTILIZER APPLICATION METHODS

As we have been discussing, wise, effective fertilizer use involves making correct decisions regarding *which* nutrient element(s) to apply, *how much* of each needed nutrient to apply, *what type* of material or carrier to use (Tables 16.9 and 16.17 list some of the choices), *in what manner* to apply the material, and, finally, *when* to apply it. We will leave information on the first two decisions until Section 16.10. Here we will discuss the alternatives available with regard to the last two decisions.

There are three general methods of applying fertilizers (Figure 16.38): (1) *broadcast application*, (2) *localized placement*, and (3) *foliar application.* Each method has some advantages and

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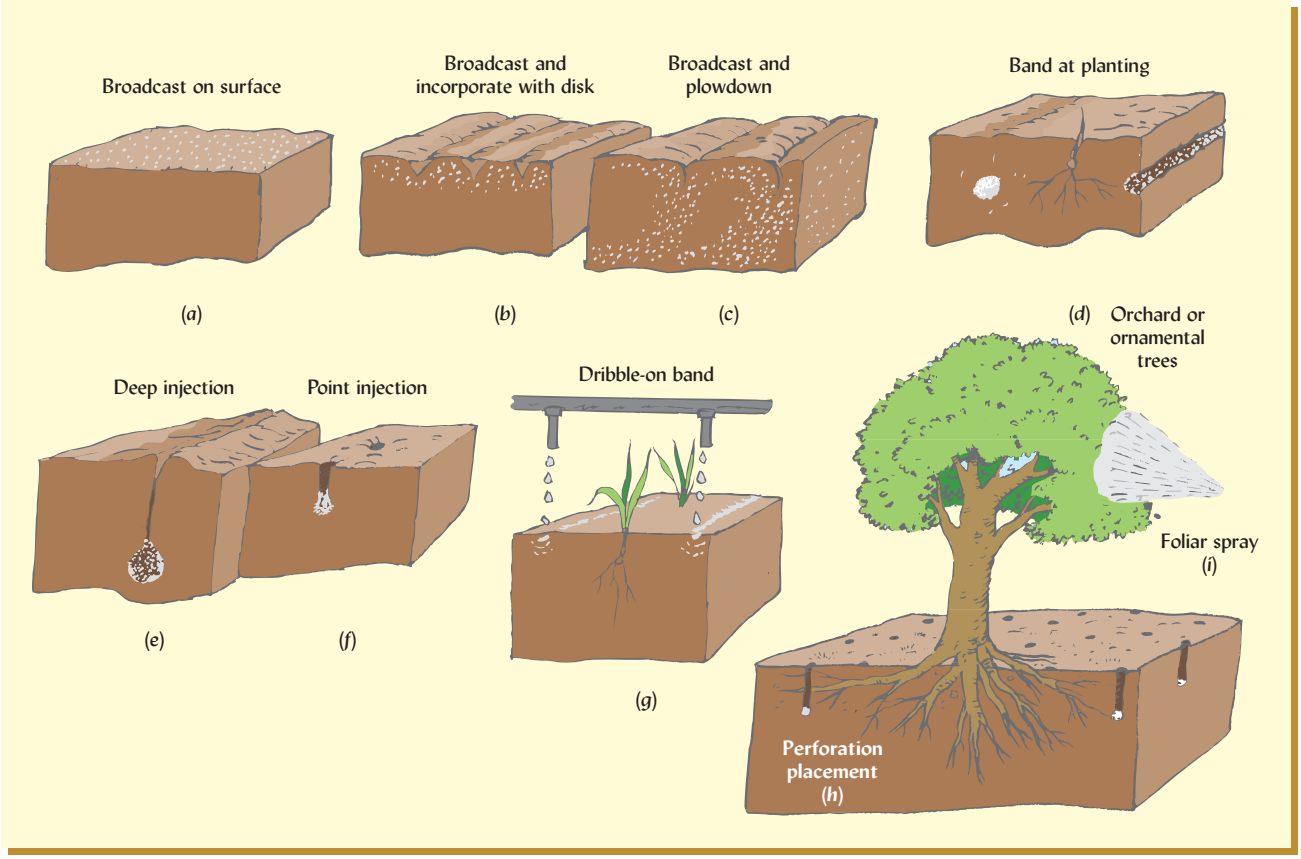

Figure 16.38 *Fertilizers may be applied by many different methods, depending on the situation. Methods (a)–(c) represent broadcast fertilizer, with or without incorporation. Methods (d)–(h) are variations of localized placement. Method (i) is foliar application and has special advantages, but also limitations. Commonly, two or three of these methods may be used in sequence. For example, a field may be prepared with (c) before planting; (d) may be used during the planting operation; (g) may be used as a side dressing early in the growing season; and, finally, (i) may be used to correct a micronutrient deficiency that shows up in the middle of the season.* (Diagram courtesy of Ray R. Weil)

disadvantages and may be particularly suitable for different situations. Often some combination of the three methods is used.

Broadcasting

In many instances fertilizer is spread evenly over the entire field or area to be fertilized. This method is called *broadcasting*. Often the broadcast fertilizer is mixed into the soil layer by means of tillage, but in some situations it is left on the soil surface and allowed to be carried into the root zone by percolating rain or irrigation water. The broadcast method is most appropriate when a large amount of fertilizer is being applied with the aim of raising the fertility level of the soil over a long period of time. Broadcasting is the most economical way to spread large amounts of fertilizer over wide areas (Figure 16.39).

For close-growing vegetation, broadcasting provides an appropriate distribution of the nutrients. It is therefore the most commonly used method for rangeland, pastures, small grains, turf grass, and forests. Fertilizers are also broadcast on some row cropland, especially in the fall when it is most convenient, although certainly not most efficient. The broadcast fertilizer may or may not be incorporated into the soil (Figure 16.38*b*,*c*). Unfortunately for crops with wide row spacing or young tree seedlings in forest plantings, broadcasting places the fertilizer where most of it is accessible more to the *weeds* than to the target plants.

For phosphorus, zinc, manganese, and other nutrients that tend to be strongly retained by the soil, broadcast applications are usually much less efficient than localized placement.

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Figure 16.39 *Broadcast fertilization. (a) Helicopter broadcasting special forestry-grade fertilizer pellets. (b) Broadcasting a nitrogen solution (mixed with fungicide) on a wheat field in France. (c) Broadcasting granular phosphorus and potassium fertilizer on a hayfield.* (Helicopter photo courtesy of Westvaco, Inc.; others courtesy of Ray R. Weil)

Often 2–3 kg of fertilizer must be broadcast to achieve the same response as from 1 kg that is placed in a localized area.

A heavy one-time application of phosphorus and potassium fertilizer, broadcast and worked into the soil, is a good preparation, where nutrients are needed, for establishing perennial plants such as lawns, pastures, and orchards. It may be necessary to broadcast a top dressing in subsequent years, being careful not to allow fertilizers with high salt hazards (see Table 16.13) to remain in contact with the foliage long enough to cause salt burn (Figure 16.40). Nitrogen is commonly broadcast in a liquid form (sprayed), often in a solution that also contains other nutrients or chemicals (see Figure 16.39*b*). Because of its mobility in the soil, nitrogen does not suffer from reduced availability when broadcast, but if left on the soil surface, much may be lost by volatilization. Volatilization losses are especially troublesome for urea and ammonium fertilizers applied to soils with a high pH. Surface broadcast nutrients are also susceptible to loss in runoff. Many studies have shown that most of the annual loss of nutrients (or herbicides, if surface broadcast) in runoff usually occurs during the first one or two heavy-rainfall events after the broadcast application. Where sprinkler irrigation is practiced, liquid fertilizers can be broadcast in the irrigation water, a practice sometimes called **fertigation**.

Localized Placement

Although it is commonly thought that nutrients must be thoroughly mixed throughout the root zone, research has clearly shown that a plant can easily obtain its entire supply of a

Figure 16.40 *Salt burn from fertilizer broadcast on plant foliage. (Left) Too much urea-ammonium nitrate solution sprayed on corn during dry weather. (Right) Dry fertilizer initially spread on home lawn at a too high rate.* (Photos courtesy of Ray R. Weil)

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nutrient from a concentrated localized source in contact with only a small fraction of its root system. In fact, a small portion of a plant's root system can grow and proliferate in a band of fertilizer even though the salinity level caused by the fertilizer would be fatal to a germinating seed or to a mature plant were a large part of its root system exposed. This finding allowed the development of techniques for localized fertilizer placement.

There are at least two reasons why fertilizer is often more effectively used by plants if it is placed in a localized concentration rather than mixed with soil throughout the root zone. First, localized placement reduces the amount of contact between soil particles and the fertilizer nutrient, thus minimizing the opportunity for adverse fixation reactions. Second, in the fertilized zone the concentration of the nutrient in the soil solution at the root surface will be very high, resulting in greatly enhanced uptake by the roots.

Localized placement is especially effective for young seedlings, in cool soils in early spring, and for plants that grow rapidly with a big demand for nutrients early in the season. For these reasons, **starter fertilizer** is often applied in bands on either side of the seed as the crop is planted. Since germinating seeds can be injured by fertilizer salts, and since these salts tend to move upward as water evaporates from the soil surface, the best placement for starter fertilizer is approximately 5 cm below and 5 cm off to the side from the seed row (see Figure 16.38*d*).

Liquid fertilizers and slurries of manure and sewage sludge can also be applied in bands rather than broadcast. Bands of these liquids are placed 10–30 cm deep in the soil by a process known as ***knife injection*** (Figures 16.38*e* and 16.41, *middle*). In addition to the advantages mentioned for banding fertilizer, injection of these organic slurries reduces runoff losses and odor problems. Anhydrous ammonia and pressurized nitrogen solutions must be injected into the soil to prevent losses by volatilization. Injecting bands at 15 and 5 cm, respectively, are considered adequate depths for these two materials.

Another approach to banding solutions (though not slurries) is to ***dribble*** a narrow stream of liquid fertilizer alongside the crop row as a side-dressing (Figure 16.41, *left*). The use of a stream instead of a fine spray changes the application from broadcast to banding and results in enough liquid in a narrow zone to cause the fertilizer to soak into the soil. This action greatly reduces volatilization loss of nitrogen.

Localized placement of fertilizer can be carried one step beyond banding with a system called ***point injection***. With this system, small portions of liquid fertilizer can be applied next to every individual plant without significantly disturbing either the plant root or the surface residue cover left by conservation tillage. The experimental point injection implements are modern versions of the age-old dibble stick with which peasant farmers in many countries traditionally plant seeds and later apply a portion of fertilizer in the soil next to each plant (Figure 16.41, *right*), all with a minimum of disturbance of the surface mulch.

Figure 16.41 (Left) *A liquid fertilizer applicator with hoses* dribbling *a stream of liquid between each row of corn as a side-dressing.* (Middle) *Manure slurry being knife-injected into the soil before planting crops on the land. This injection method reduces runoff losses and objectionable odors.* (Right) *A measured* micro dose *of solid fertilizer granules being applied by hand as a dollop in a small hole near a young crop plant in Africa.* (Photos courtesy of Ray R. Weil)

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The use of ***drip irrigation*** systems (see Section 6.9) has greatly facilitated the localized application of nutrients in irrigation water. Because drip fertigation is applied at frequent intervals, the plants are essentially spoon-fed, and the efficiency of nutrient use is quite high.

Perforation Method for Trees. Trees in orchards and ornamental plantings are best treated individually, the fertilizer being applied around each tree within the spread of the branches but beginning approximately 1 m from the trunk (see Figure 16.38*b*). The fertilizer is best applied by what is called the *perforation* method. Numerous small holes are dug around each tree within the outer half of the branch-spread zone and extending down into the upper subsoil where the fertilizer is placed. Special large fertilizer pellets are available for this purpose. This method of application places the nutrients within the tree root zone and avoids an undesirable stimulation of the grass or cover that may be growing around the trees. If the cover crop or lawn around the trees needs fertilization, it is treated separately, the fertilizer being drilled in at the time of seeding or broadcast later.

Foliar Application

Plants are capable of absorbing nutrients through their leaves in limited quantities. Under certain circumstances, the best way to apply a nutrient is *foliar application*—spraying a dilute nutrient solution directly onto the plant leaves (Figure 16.38*i*). Diluted macronutrient fertilizers, micronutrients, or small quantities of urea can be used as foliar sprays, although care must be taken to avoid significant concentrations of salts, especially Cl^- or NO_3^-, which can be toxic to some plants. Foliar fertilization may conveniently fit in with other field operations for horticultural crops, because the fertilizer is often applied simultaneously with pesticide sprays.

The amount of nutrients that can be sprayed on leaves in a single application is quite limited. Therefore, while a few spray applications may deliver the entire season's requirement for a micronutrient, only a small portion of the macronutrient needs can be supplied in this manner. The danger of leaf injury (Figure 16.40, *left*) is especially high during dry, hot weather, when the solution quickly evaporates from the leaf surface, leaving behind the fertilizer salts. Spraying on cool, overcast days or during early morning or late evening hours reduces the risk of injury, as does the use of a dilute solution containing, for example, only 1 or 2% nitrogen.

16.9 TIMING OF FERTILIZER APPLICATION

The timing of nutrient applications in the field is governed by several basic considerations: (1) making the nutrient available when the plant needs it; (2) avoiding excess availability, especially of nitrogen, before and after the principal period of plant uptake; (3) making nutrients available when they will strengthen, not weaken, long-season and perennial plants; and (4) conducting field operations when conditions make them practical and feasible.

Availability When the Plants Need It

For mobile nutrients such as nitrogen (and to a lesser degree sulfur and potassium), the general rule is to make applications as close as possible to the period of rapid plant nutrient uptake. For rapid-growing summer annuals, such as corn, this means making only a small starter application at planting time and applying most of the needed nitrogen as a side dressing just before the plants enter the rapid nutrient accumulation phase, usually about four to six weeks after planting. For cool-season plants, such as winter wheat or certain turf grasses, most of the nitrogen should be applied about the time of spring "green-up," when the plants resume a rapid growth rate. For trees, the best time is when new leaves are forming. With slow-release organic sources, time should be allowed for mineralization to take place prior to the plants' period of maximum uptake.

Environmentally Sensitive Periods

In temperate (**Udic** and **Xeric**) climates, most leaching takes place in the winter and early spring when precipitation is high and evapotranspiration is low. Nitrates left over or released after plant

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uptake has ceased have the potential for leaching during this period. In this regard it should be noted that, for grain crops, the rate of nutrient uptake begins to decline during grain-filling stages and has largely or completely ceased long before the crop is ready for harvest. With inorganic nitrogen fertilizers, avoiding leftover nitrates is largely a matter of limiting the amount applied to what the plants are expected to take up. However, for slow-release organic sources applied in late spring or early summer, mineralization is likely to continue to release nitrates after the crop has matured and ceased taking them up. To the extent that this timing of nitrate release is unavoidable, cover crops should be planted as soon as possible after the summer crop's nitrogen uptake has slowed in order to absorb the excess nitrate being released.

Split Applications. In high-rainfall conditions and on permeable soils, dividing a large dose of fertilizer into two or more split applications may avoid leaching losses prior to the crop's establishment of a deep root system. In cold climates, another environmentally sensitive period occurs during early spring, when snowmelt over frozen or saturated soils results in torrents of runoff water. This runoff may pollute rivers and streams with soluble nutrients that are near or at the soil surface.

Application of urea fertilizers to mature forests is usually carried out when rains can be expected to wash the nutrients into the soil and minimize volatilization losses. Furthermore, nitrogen fertilization of forests should occur just prior to the onset of the growing season (early spring, or in warm climates, winter) so that the tree roots will have the entire growing season to utilize the nitrogen. Fertilizer applications commonly result in a pulse of nitrate leaving the watershed for several weeks following the fertilizer application. The nitrogen loss can be reduced if a 10- to 15-m unfertilized buffer is maintained along all streams.

Physiologically Appropriate Timing

It is important to make nutrients available when they will strengthen plants and improve their quality. For example, too much nitrogen in the summer may stress cool-season turfgrasses, while high nitrogen late in the season will reduce the sugar content of root crops. A good supply of potassium is particularly important in the fall to enable plants to improve their winter-hardiness. Planting-hole or broadcast application of phosphorus at the time of the tree planting brings good results on phosphorus-poor sites. However, broadcast application of nitrogen to trees soon after the seedlings are planted may benefit fast-growing weeds more than the desired trees. Later in the development of a forest stand, when the tree canopy has matured, application of fertilizer, usually from a helicopter, can be quite beneficial.

Practical Field Limitations

Sometimes it is simply not possible to apply fertilizers at the ideal time of the year. For example, although a crop may respond to a late-season side dressing, such an application will be difficult if the plants are too tall to drive over without damaging them. Using an airplane may allow more flexibility in fertilizer timing. Early spring applications may be limited by the need to avoid compacting wet soils. Economic costs or the time demands of other activities may also require that compromises be made in the timing of nutrient application.

16.10 DIAGNOSTIC TOOLS AND METHODS[8]

There are three basic tools available for diagnosing soil fertility problems: (1) *field observations*, (2) *plant tissue analysis*, and (3) *soil analysis* (soil testing). All three approaches should be integrated to effectively guide the application of nutrients, as well as to diagnose problems as they arise in the field. There is no substitute for careful observation and *recording* of circumstantial evidence and symptoms in the field. Effective observation and interpretation requires skill and experience, as well as an open mind. It is not uncommon for a supposed soil fertility

[8]For detailed discussions of both plant analysis and soil testing, see Jones Jr. (2012).

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problem to actually be caused by soil compaction, weather conditions, pest damage, or human error. The task of the diagnostician is to use all the tools available in order to identify the factor that is limiting plant growth, and then devise a course of action to alleviate the limitation.

Plant Symptoms and Field Observations

This detective-like work can be one of the more exciting and challenging aspects of nutrient management. To be an effective soil fertility diagnostician, several general guidelines are helpful.

1. Develop an organized way to *record* your observations. The information you collect may be needed to properly interpret soil and plant analytical results obtained at a later date.
2. Talk to the person who owns or manages the land. Ask when the problem was first observed and if any recent changes have taken place. Obtain records on plant growth or crop yield from previous years, and ascertain the history of management of the site for as many years as possible. It is often useful to sketch a map of the site showing features you have observed and the distribution of symptoms.
3. Look for *spatial patterns*—how the problem seems to be distributed in the landscape and in individual plants. Linear patterns across a field may indicate a problem related to tillage, drain tiles, or the incorrect spreading of lime or fertilizer. Poor growth concentrated in low-lying areas may relate to the effects of soil aeration. Poor growth on the high spots in a field may reflect the effects of erosion and possibly exposure of subsoil material with an unfavorable pH. Satellite images, such as those freely available from Google Earth®, may show patterns of vegetation, soils and other patterns that help explain patterns seen on the ground and can provide an excellent map base for your observations.
4. Closely examine individual plant leaves to characterize any foliar symptoms. Nutrient deficiencies can produce characteristic symptoms on leaves and other plant parts. Examples of such symptoms are shown in several figures in Chapters 13–15. Determine whether the symptoms are most pronounced on the younger leaves (as is the case for sulfur and most of the micronutrient cations) or on the older leaves (as is the case for nitrogen, potassium, and magnesium). Some nutrient deficiencies are quite reliably identified from foliar symptoms, while others produce symptoms that may be confused with herbicide damage, insect damage, or damage from poor aeration.
5. Observe and *measure* differences in *both* aboveground and belowground plant growth that may reflect different levels of soil fertility, even though no leaf symptoms are apparent. Use a shovel to dig down to at least the depth of deepest tillage or the upper subsoil layer. Dig up a few of the ailing plants and a few of the more normal plants to compare their root systems. Are mycorrhizae associated with tree roots? Are legumes well nodulated? Is root growth restricted in any way? Are roots thin, flexible, and white (as healthy root appear), or are they thickened, stubby, brittle, and brown? Do roots grow smoothly and vertically or do they hit a soil layer and abruptly turn horizontally, indicating a compacted or cemented zone.

Plant Analysis[9]

Nutrient Concentrations. The concentration of essential elements in plant tissue is related to plant growth or crop yield, as shown in Figure 16.42. The range of tissue concentrations at which the supply of a nutrient is sufficient for optimal plant growth is termed the **sufficiency range**. At the upper end of the sufficiency range, plants may be participating in luxury consumption, as the additional nutrient uptake has not produced additional plant growth (see Section 14.13). At concentrations above the sufficiency range, plant growth may decline as nutrient elements reach con-

[9]Detailed information on tissue analysis for a large number of plant species can be found in Reuter and Robinson (1986).

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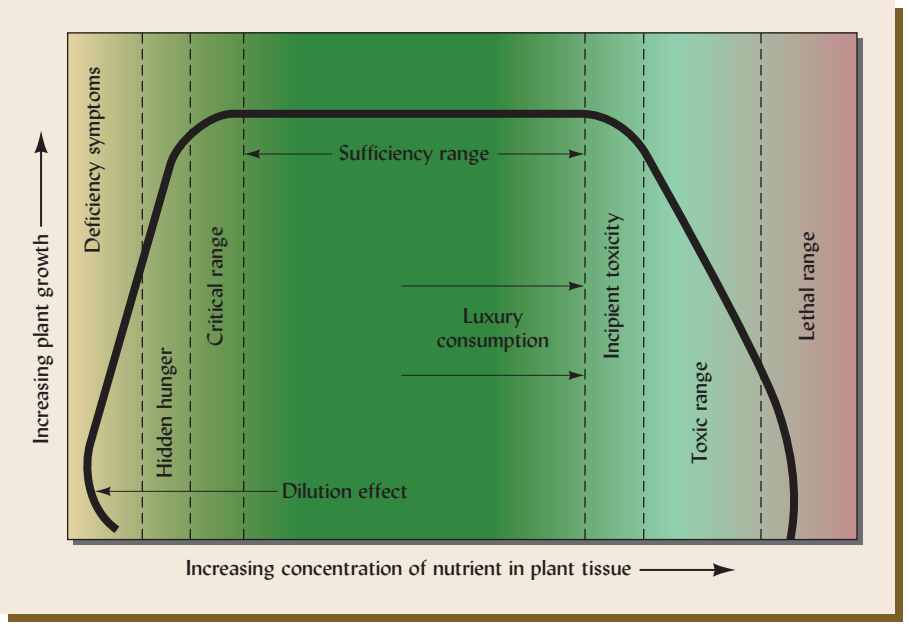

Figure 16.42 *The relationship between plant growth or yield and the concentration of an essential element in the plant tissue. For most nutrients there is a relatively wide range of values associated with normal, healthy plants (the sufficiency range). Beyond this range, plant growth suffers from either too little or too much of the nutrient. The critical range (CR) is commonly used for the diagnosis of nutrient deficiency. Nutrient concentrations below the CR are likely to reduce plant growth even if no deficiency symptoms are visible. This moderate level of deficiency is sometimes called* hidden hunger. *The dilution effect is often observed when extremely deficient plants are given a small dose of the limiting nutrient. The growth response may be so great that even though somewhat more of the element is taken up, it is diluted in a much greater plant mass.* (Diagram courtesy of Ray R. Weil)

centrations that are toxic to plant cells or interfere with the use of other nutrients. If tissue concentrations are in the **critical range**, the supply is just marginal and growth is expected to decline if the nutrient becomes any less available, even though visible foliar symptoms may not be exhibited ("hidden hunger"). Plants with tissue concentrations below the sufficiency range for a nutrient element are likely to respond to additions of that nutrient if no other factor is more limiting. The sufficiency range and critical range have been well characterized for many plants, especially for agronomic and major horticultural crops. Less is known about forest trees and ornamentals. Sufficiency ranges for 11 essential elements in a variety of plants are listed in Table 16.15.

Tissue Analysis.[10] Tissue analysis can be a powerful tool for identifying plant nutrient problems if several simple precautions are taken. First, it is critical that the correct plant part be sampled. Second, the plant part must be sampled at the specified stage of growth, because the concentrations of most nutrients decrease considerably as the plant matures. Third, it must be recognized that the concentration of one nutrient may be affected by that of another nutrient, and that sometimes the ratio of one nutrient to another (e.g., Mg/K, N/S, or Fe/Mn) may be the most reliable guide to plant nutritional status (Figure 16.43). In fact, several elaborate mathematical systems for assessing the ratios or balance among nutrients have proven useful for certain plant species. Because of the uncertainties and complexities in interpreting tissue concentration data, it is wise to sample plants from the best and worst areas in a field or stand. The difference between samples may provide valuable clues concerning the nature of the nutrient problem.

Cornstalk Nitrate. The *end-of-season cornstalk nitrate test* (CSNT) measures the nitrate content of the lower portion of mature cornstalks at harvest time. Four categories have been defined [expressed as mg of nitrate-N/kg dry cornstalk: deficient (<250), marginal (250–700), optimal (700–2000), and excessive (>2000)]. This is a "post-mortem" test that can be used to improve future nitrogen management for corn. This test is particularly helpful in identifying excessive levels of nitrogen in the plant at harvest time, which, in turn, is an indication of excessive levels in the soil at the end of the season. Such high cornstalk nitrate levels alert farmers to reduce their nitrogen applications to avoid excess nitrogen leaching in future years.

[10]The best developed of the multinutrient ratio systems is known as the Diagnostic Recommendation Integrated System (DRIS). For details, see Serra et al. (2013).

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Table 16.15
A Guide to Sufficiency Ranges for Tissue Analysis of Selected Plant Species
Values apply only to the indicated plant parts and stage of growth. Normally, 6–20 plants should be sampled. Leaves should be washed briefly in distilled water to remove any soil or dust and then dried before submitting for analysis.

		Content, %					Content, µg/g				
Plant species and part to sample	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**B**	**Cu**
Pine trees (*Pinus* spp.) Current-year needles near terminal	1.2–1.4	0.10–0.18	0.3–0.5	0.13–0.16	0.05–0.09	0.08–0.12	20–100	50–600	20–50	3–9	2–6
Oak tree (*Quercus*) Mature leaves	1.9–3.0	0.15–0.30	1.0–1.5	0.3–0.5	0.15–0.30	0.18–0.25	50–150	35–200	15–30	15–40	6–12
Turfgrasses, warm season Clippings	2.7–3.5	0.25–0.55	1.3–3.0	0.50–1.2	0.15–0.60	0.15–0.6	35–500	25–150	15–55	6–60	5–30
Turfgrasses, cool season Clippings	3.0–5.0	0.3–0.4	2–4	0.3–0.8	0.2–0.4	0.25–0.8	40–500	20–100	20–50	5–20	6–30
Corn (*Zea mays*) Ear-leaf at tasseling	2.5–3.5	0.20–0.50	1.5–3.0	0.2–1.0	0.16–0.40	0.16–0.50	25–300	20–200	20–70	6–40	6–40
Soybean (*Glycine max*) Youngest mature leaf at flowering	4.0–5.0	0.31–0.50	2.0–3.0	0.45–2.0	0.25–0.55	0.25–0.55	50–250	30–200	25–50	25–60	8–20
Apple (*Malus* spp.) Leaf at base of nonfruiting shoots	1.8–2.4	0.15–0.30	1.2–2.0	1.0–1.5	0.25–0.50	0.13–0.30	50–250	35–100	20–50	20–50	5–20
Wheat (*Triticum* spp.) Youngest mature leaf at flowering	2.2–3.3	0.24–0.36	2.0–3.0	0.28–0.42	0.19–0.30	0.20–0.30	35–55	30–50	20–35	5–10	6–10
Rice (*Oryza sativa*) Youngest mature leaf at tillering	2.8–3.6	0.14–0.27	1.5–3.0	0.16–0.40	0.12–0.22	0.17–0.25	90–200	40–800	20–160	5–25	6–25
Tomato (*Solanum lycopersicum*) Youngest mature leaf at flowering	3.2–4.8	0.32–0.48	2.5–4.2	1.7–4.0	0.45–0.70	0.60–1.0	120–200	80–180	30–50	35–55	8–12
Alfalfa (*Medicago sativa*) Upper third of plant at first flower	3.0–4.5	0.25–0.50	2.5–3.8	1.0–2.5	0.3–0.8	0.3–0.5	50–250	25–100	25–70	6–20	30–80

Data derived from many sources.

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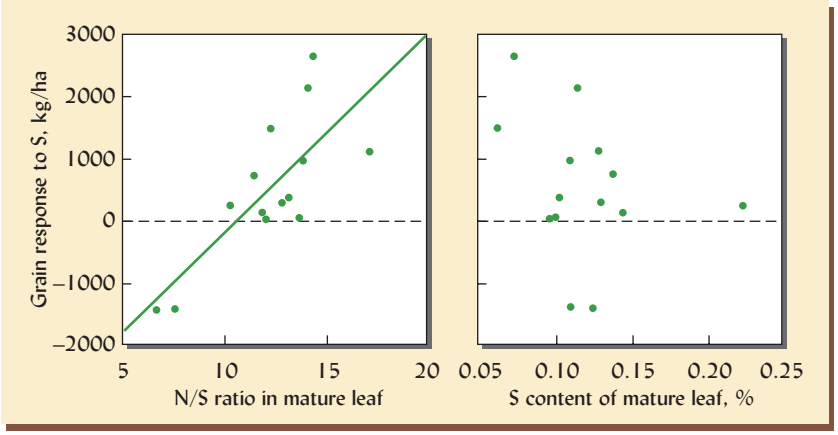

Figure 16.43 *Relationship between the corn grain response to sulfur application and the corn leaf sulfur content (right) or the N/S ratio (left). The graphs illustrate that the ratio of two interacting elements is often a better guide to plant nutrient status than the tissue contents of either element alone. Nitrogen and sulfur are both needed to synthesize plant proteins. As the N/S ratio of the unfertilized corn increased, so did the positive response to application of sulfur (as gypsum). There was no clear relationship between response to sulfur application and the leaf sulfur content by itself, even though most of the corn had sulfur levels below the sufficiency range indicated in Table 16.15. The data are from experiments on 14 small farms in Malawi. Sulfur deficiencies are widespread in African soils.* (Graphed from data in Weil and Mughogho (2000))

On-the-Spot Plant Sap Analysis. Healthy, well-fed plants will take up nutrients faster than metabolic processes can assimilate the elements into plant molecules. Therefore, certain nutrients may accumulate in the plant sap as they await assimilation. The sap can be squeezed from plant stems or leaf petioles and analyzed for its content of the dissolved nutrient elements to assess the sufficiency of the nutrient supplies. While nutrients in the sap can be determined in the lab, recent advances have allowed reasonably accurate measurement of sap nutrients to be made in the field immediately after picking the plant parts (Figure 16.44). Of course, the nutrient concentrations in the sap are meaningful only if research data are available that relate the measured levels to plant growth and health. Reference values for desirable concentration ranges are available online mainly for high value vegetable crops. Nutrient concentrations in sap can vary widely with plant growth stage and with weather conditions. For example, nitrate-N may accumulate to very high levels in sap if cloudy, cool weather slows photosynthesis of the carbon chains needed to assimilate nitrate into protein or chlorophyll. A few hours of warm, sunny conditions could reverse the accumulation and lower the sap nitrate-N level. Interpretation of sap data must take into account the conditions of growth during and just before the sampling.

Measurement of Plant Leaf "Greenness." Chlorophyll molecules comprise the pigments that absorb the light that plants use in photosynthesis, but do not absorb green light, hence leaves both reflect and transmit green light, giving them the green color we see. Chlorophyll concentration and therefore the greenness of a leaf is often determined by the plant's nitrogen

Figure 16.44 *Analysis of plant sap in the field. Plant stems or leaf petioles are chopped into small pieces (left) and then squeezed to express a few drops of sap (middle) which is then placed on an ion selective sensor to determine the concentrations of such ions as NO_3^- or K^+. Reference values for sap NO_3^- and K, as well as tissue analysis norms for those and other elements are given for vegetable crops in Hochmuth et al. (2012).* (Photos courtesy of Ray R. Weil)

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supply, nitrogen-limited plants exhibiting somewhat lighter or yellower green colors. While other environmental stresses such as sulfur deficiency or water stress can also make leaves less green, the nitrogen-greenness correlation has proven to be a practical indication of the nitrogen status of plants in the field. Meters have been developed that shine a spectrum of light at or through a leaf and then detect the transmitted or reflected wavelengths of light using sensors especially sensitive to near and far infrared wavelengths. The near infrared light (about 650 nm) is strongly absorbed by chlorophyll while the far infrared (about 940 nm) serves as a reference that compensates for variations in leaf thickness, water content, orientation, etc. In this way, the meter can discriminate among different levels of leaf greenness with much more accuracy than the human eye. Such meters (sometimes referred to as SPAD meters) can be clamped onto a single leaf for diagnosis of a plants nitrogen status. Similar meters (referred to as on-the-go-chlorophyll sensors) can also be mounted in front of fertilizer spraying equipment and send signals to a computer that controls the rate of fertilizer application, such that small areas of lighter green (nitrogen hungry) plants can be given more nitrogen while areas of darker green plants (already well supplied with nitrogen) are given less.

We have just considered some of the many technologies by which plants are used to evaluate the nutrient supplying power of soil. We will now consider methods that attempt to more directly measure nutrients in the soil.

16.11 SOIL ANALYSIS

Since the total amount of a nutrient element in a soil tells us very little about the ability of that soil to supply that element to plants, more meaningful *partial soil analyses* have been developed. *Soil testing* is the routine partial analysis of soils for the purpose of guiding nutrient management.

The soil testing process consists of three critical phases: (1) *sampling* the soil, (2) chemically *analyzing* the sample, and (3) *interpreting* the analytical result to make a recommendation on the kind and amounts of nutrients to apply.

Sampling the Soil

Soil sampling is widely acknowledged to be one of the weakest links in the soil testing process. Part of the problem is that about a teaspoonful of soil (Figure 16.45) is eventually used to represent millions of kilograms of soil in the field. Since soils are highly variable, both

Figure 16.45 *In the testing lab, soil samples are ground and screened to make a homogenous powder, a small portion of which is scooped or weighed (inset) for analysis. This small amount of soil must represent thousands of tons of soil in the field. After a portion of the nutrients has been extracted from the soil sample, the solution containing these nutrients undergoes elemental analysis. Since soil test labs must run hundreds or thousands of samples each day, the analysis is generally automated and the results are recorded and interpreted by computer.* (Photos courtesy of Ray R. Weil)

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horizontally and vertically, it is essential to carefully follow the sampling instructions from the soil testing laboratory.

Because of the variability in nutrient levels from spot to spot, it is always advisable to divide a given field or property into as many distinct areas as practical, taking soil samples from each to determine nutrient needs. For example, suppose a 20-ha field has a 2-ha low spot in the middle, and 5 ha at one end that used to be a permanent pasture. These two areas should be sampled, and later managed, separately from the remainder of the field. Similarly, a homeowner should sample flower beds separately from lawn areas, low spots separately from sloping areas, and so on. On the other hand, known areas of unusual soil that are too small or irregular to be managed separately should be avoided and not included in the **composite sample** representing the whole field.

Composite Sample. Usually, a soil probe is used to remove a thin cylindrical core of soil from at least 12–15 randomly scattered places within the land area to be represented (Figure 16.46). The 12–15 subsamples are thoroughly mixed in a plastic bucket, and about 250 g of the soil is placed in a labeled container and sent to the lab. If the soil is moist, it should be air-dried without sun or heat prior to packaging for routine soil tests. Heating the sample might cause a falsely high result for certain nutrients.[11]

Two questions must be addressed when sampling a soil: (1) the depth to which the sample should be taken, and (2) the time of year when the soil should be sampled.

Depth to Sample. The standard depth of sampling for a plowed soil is the minimum depth of the plowed layer, about 15–20 cm, but various other depths are also used (see Figure 16.46). Because in many unplowed soils nutrients are stratified in contrasting layers, the depth of sampling can greatly alter the results obtained. Whatever depth of sampling is decided upon, it is critical that each sub-sample core contributing to the composite sample be of that precise depth.

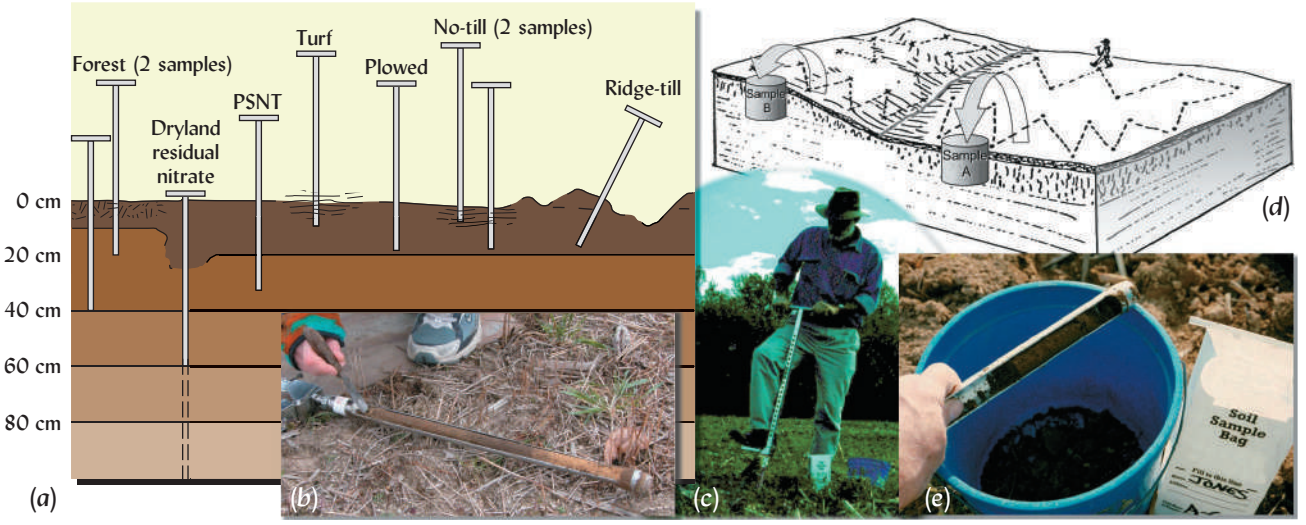

Figure 16.46 *Taking a proper soil sample in the field is often the most critical and error-prone step in the soil testing process. (a) The proper depth to sample depends on the purpose of the soil test and the nature of the soil. Some suggested depths for different situations are shown. (b) An open-sided soil probe containing 40 cm long soil core is about to be cut into separate depth increments. It would not be a good idea for a sample to straddle the boundary between the A and B horizons as indicated here by the abrupt color change. (c) A soil probe with a long handle and foot step makes sampling easier, especially for deep samples or in hard soils. (d) Collecting 10–20 subsample cores for each sample sent to the lab is essential, even in a uniform-appearing area. Unusual areas (wet spots, places where manure was piled, eroded spots, etc.) should be avoided. (e) A 15 cm soil core being added to others in a plastic bucket. The cores will be crumbled and mixed in the bucket before a portion of about 250 g is placed in the sample bag for transport to the lab.* (Photos and diagrams courtesy of Ray R. Weil)

[11]Samples for analysis of soil nitrates should be rapidly dried under a fan or in an oven at about 65 °C.

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Time of Year. Seasonal changes are often observed in soil test results for a given area. For example, the potassium level is usually highest in early spring, after freezing and thawing has released some fixed K ions from clay interlayers, and lowest in late summer, after plants have removed much of the readily available supply. The time of sampling is especially important if year-to-year comparisons are to be made. A good practice is to sample each area every year or two (always at the same time of year), so that the soil test levels can be tracked over the years to determine whether nutrient levels are being maintained, increased, or depleted.

Timing for Special Nitrogen Tests. Timing is especially critical to determine the amount of mineralized nitrogen in the root zone. In relatively dry, cold regions (e.g., Canadian northern Great Plains and the United States), a *residual nitrate* test is done on 60-cm-deep samples obtained sometime between fall and before planting in spring. In humid regions, where nitrate leaching is more pronounced, a special test has been developed to determine whether nitrogen is mineralizing rapidly enough to supply a crop's needs. This test, termed the *pre-sidedress nitrate test* (PSNT) is usually performed in the late spring to help predict the amount of nitrogen needed for the summer growing season, but can also be applied in the late summer for fall and overwintering crops. For the PSNT samples are composited from the upper 30 cm of soil at a time when a young crop is about to enter its period of most rapid growth and nitrogen uptake (e.g., when corn is about 30 cm tall).

The PSNT has proven quite accurate in predicting the amount of additional nitrogen that would be most profitable to apply to the crop growing in a given field. However, conducting the PSNT is very labor intensive and must be accomplished during the rather narrow window of time when spring mineralization has peaked, but plant uptake has not yet begun to deplete the nitrate produced (see Figure 13.11). The time, labor, and cost constraints associate with the PSNT have spurred researchers to develop computer models that use detailed weather and soil data to predict the progress of soil nitrogen mineralization in a given field without having to actually sample the soil and measure it. These limitations also make it impractical to use the PSNT for mapping out different portions of a field that may need more or less nitrogen than the average. In this regard, the measurement of light reflected from or transmitted by plant foliage, as discussed in Section 16.10, offers a greater potential to allow different parts of a field to be treated with varying amounts of nitrogen according to spatial variations in soil N availability.

Site-Specific Management Zones. The just-described standard procedure of mixing many small soil samples into a single composite sample to represent the "average" soil in a large field must be recognized for the compromise that it is. Fertilizer recommendations based on the *average* soil condition in the field will likely be either too high or too low for almost any particular spot in that field. Using *geographic information systems* (GIS) computer technology, fertilizer rates can be much more precisely tailored to account for soil variations within a field. However, the benefits of doing this are not always worth the costs. The costs include field labor and fees for obtaining, processing, and analyzing a large number of composite soil samples collected in a grid pattern within the field. Since each sample is geo-referenced as to its specific location (using space satellite–based *geo-positioning systems*, GPS), computer software can generate maps showing management zones with defined soil properties and fertilizer needs. The maps can then be fed into computer-controlled fertilizer-spreading equipment that can adjust the rates of application as they drive across a field to spread more or less fertilizer as called for by the map of management zones. The development and use of this type of spatial information about soils will be discussed in more detail in Section 19.9.

Chemical Analysis of the Sample

In general, soil tests attempt to extract from the soil amounts of essential elements that are correlated with the nutrients taken up by plants during a growing season. Different extraction solutions are employed by various laboratories. Buffered salt solutions, such as sodium or ammonium acetate, or mixtures of dilute acids and chelating agents are the extracting agents most commonly used. The extractions are accomplished by placing a small measured quantity of soil in a bottle with the extracting agent and shaking the mixture for a certain number of minutes. The amount of the various nutrient elements brought into solution is then

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determined. The whole process is usually automated so that a modern laboratory can handle hundreds or thousands of samples each day (see Figure 16.45).

The most common and reliable tests are those for soil pH, potassium, phosphorus, and magnesium. Micronutrients are sometimes extracted using synthetic chelating agents that mimic the metal-binding action of root and microbial compounds. Chelating agents are especially important for testing calcareous soils in the more arid regions.

Testing for the nitrogen and sulfur supplying capacity of soils is particularly troublesome. While the nitrate and sulfate present in the soil at the time of sampling can be measured, this "snapshot" is unlikely to predict the availability of nitrogen and sulfur during the growing season because of the many weather-dependent biological processes involved in the mineralization of these elements from soil organic matter. Some progress is being made in developing laboratory tests that combine a measure of microbial activity (such as CO_2 respiration rate) with measures of organic N content to predict potential N mineralization.

Because the methods used by different labs may be appropriate for different types of soils, it is advisable to send a soil sample to a lab in the same region from which the soil originated. Such a lab is likely to use procedures appropriate for the soils of the region and should have access to data correlating the analytical results to plant responses on soils of a similar nature.

Mehlich 3 Extract. Although many different extracting solutions are still in use by various soil-testing labs, a solution known as the "Mehlich 3 extractant" deserves special mention as this method has recently gained wide acceptance (especially in humid regions) as a nearly "universal" soil test extractant.[12] This complex extracting solution contains 0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.15 *M* NH_4F + 0.013 *M* HNO_3 + 0.001 *M* EDTA. These components allow the extractant to remove "plant-available" nutrients from soils by the processes of dissolution (by the acids), desorption (by the NH_4F and NH_4NO_3), and chelation (by the EDTA). In this method, a measured volume (2.5 cm^3) of dry, sieved soil is shaken with 100 mL of the extracting solution for 5 minutes, and then filtered. The filtrate can be analyzed for almost all of the essential elements, usually by an automated inductively coupled plasma (ICP) emission spectrograph, which is capable of determining dozens of elements in a single analysis.

Soil tests designed for use on soils or soil-based potting media generally do not give meaningful results when used on artificial peat-based soilless potting media. Special extraction procedures must be used for the latter, and the results must then be correlated to nutrient uptake and growth of plants grown in similar media.

These examples should further emphasize the importance of providing the soil testing lab with complete information concerning the nature of your soil, its management history, and your plans for its future use.

Interpreting the Results to Make a Recommendation

This is, perhaps, the most controversial aspect of soil testing. The soil test values themselves are merely *indices* of nutrient-supplying power. They do not indicate the actual amount of nutrient that will be supplied. For this reason, it is best to think of soil test reports as more indicative than quantitative.

Many years of field experimentation at many sites are needed to determine which soil test levels indicate low, medium, or high capacities to supply the nutrient tested. Such categories are used to predict the likelihood of obtaining a profitable response from the application of a particular nutrient (Figure 16.47). Since the actual units of measurement (ppm, mg/L, kg/ha, or lb/acre) have little meaning with regard to evaluating the soil nutrient supplying capacity, soil test results are increasingly reported as index values on a relative scale (often with 75–100 considered optimal). The report shown in Figure 16.48 uses both interpretative categories and a relative index scale.

Recommendations for nutrient applications take into consideration practical knowledge of the plants to be grown, the characteristics of the soil under study, and other environmental conditions. Management history and field observations can help relate soil test data to fertilizer needs.

[12] *After* he had officially retired from North Carolina State University, Dr. A. Mehlich developed the Mehlich 3 extractant, the third and most successful of his soil test methods. See Mehlich (1984).

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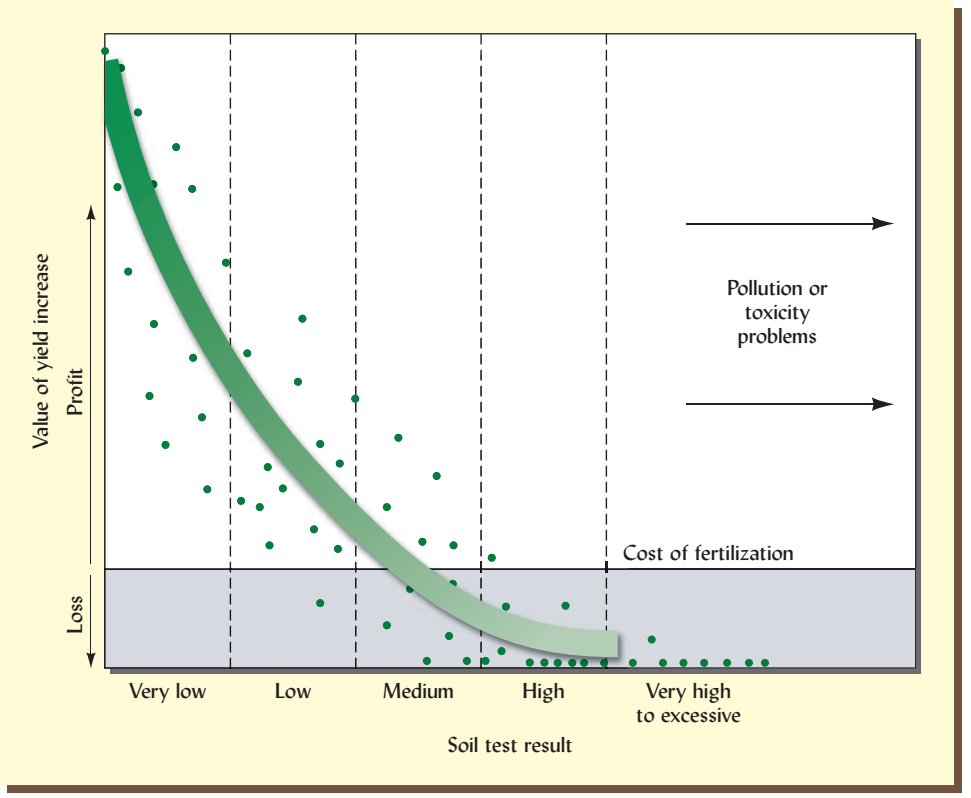
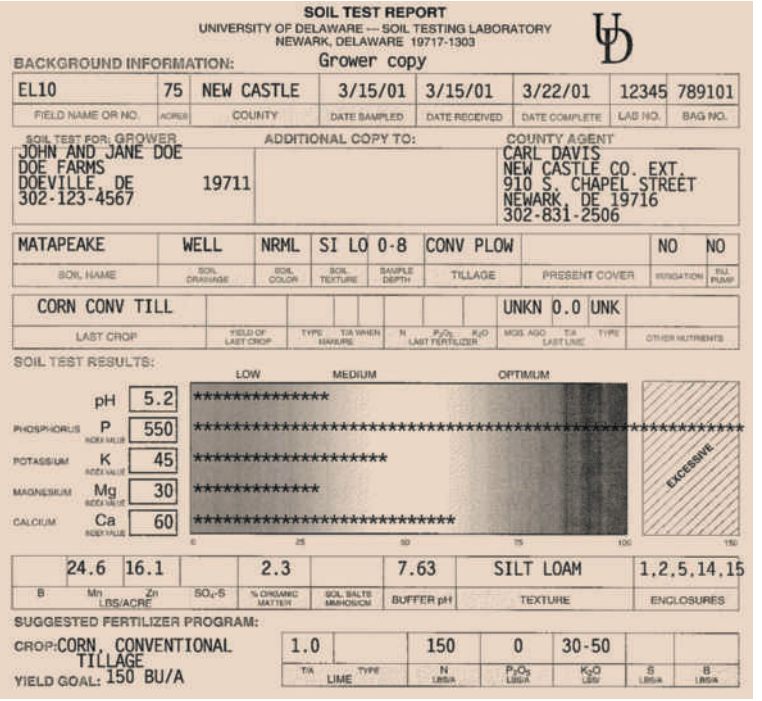


Figure 16.47 *The relationship between soil test results for a nutrient and the extra yield obtained by fertilizing with that nutrient. Each data point represents the difference in plant yield between fertilized and the unfertilized plots at one location in one year. Because many factors affect yield and because soil tests can only approximately predict nutrient availability, the relationship is not precise, but the data points are scattered about the trend line. If the point falls above the fertilizer cost line, the extra yield was worth more than the cost of fertilizing and a profit would be made. For a soil testing in the very low and low categories, a profitable response to fertilizer is very likely. For a soil testing medium, a profitable response is a 50:50 proposition. In the high category, a profitable response is unlikely.* (Diagram courtesy of Ray R. Weil)

The interpretation of soil test data is best accomplished by experienced and technically trained personnel who fully understand the scientific principles underlying the common field procedures. In most commercial or university soil test laboratories, the factors to be considered in making fertilizer recommendations are programmed into a computer, and the interpretation is printed out for use by the land manager (Figure 16.48).



SOIL TEST REPORT
UNIVERSITY OF DELAWARE — SOIL TESTING LABORATORY
NEWARK, DELAWARE 19717-1303

BACKGROUND INFORMATION: Grower copy

FIELD NAME OR NO.	ACRES	COUNTY	DATE SAMPLED	DATE RECEIVED	DATE COMPLETE	LAB NO.	BAG NO.
EL10	75	NEW CASTLE	3/15/01	3/15/01	3/22/01	12345	789101

SOIL TEST FOR: GROWER
JOHN AND JANE DOE
DOE FARMS
DOEVILLE, DE 19711
302-123-4567

ADDITIONAL COPY TO:

COUNTY AGENT
CARL DAVIS
NEW CASTLE CO. EXT.
910 S. CHAPEL STREET
NEWARK, DE 19716
302-831-2506

SOIL NAME	SOIL DRAINAGE	SOIL COLOR	SOIL TEXTURE	SAMPLE DEPTH	TILLAGE	PRESENT COVER	IRRIGATION	PU PUMP
MATAPEAKE	WELL	NRML	SI LO	0-8	CONV PLOW		NO	NO

LAST CROP	YIELD OF LAST CROP	TYPE	T/A WHEN MANURE	N	P_2O_5	K_2O	LAST FERTILIZER	MOS. AGO	T/A	TYPE	LAST LIME	OTHER NUTRIENTS
CORN CONV TILL								UNKN	0.0	UNK		

SOIL TEST RESULTS:

			LOW	MEDIUM	OPTIMUM	
	pH	5.2	**********			
PHOSPHORUS	P	550	**********	**********	**********	EXCESSIVE
POTASSIUM	K	45	**********	**********		
MAGNESIUM	Mg	30	**********			
CALCIUM	Ca	60	**********	**********		

B	Mn	Zn	SO_4-S	% ORGANIC MATTER	SOIL SALTS MMHOS/CM	BUFFER pH	TEXTURE	ENCLOSURES
	24.6	16.1	2.3		7.63		SILT LOAM	1,2,5,14,15

LBS/ACRE

SUGGESTED FERTILIZER PROGRAM:

CROP: CORN, CONVENTIONAL TILLAGE
YIELD GOAL: 150 BU/A

T/A	LIME	TYPE	N LBS/A	P_2O_5 LBS/A	K_2O LBS/A	S LBS/A	B LBS/A
1.0			150	0	30-50		

Figure 16.48 *A typical soil test giving results as index values spanning such categories as low, medium, and optimum or high. The report includes the nature and history of the field, extractable levels of certain nutrients and soil properties that were measured in the lab, and recommendations for the amounts and types of soil amendments to apply for a specific crop. For this particular field, the following interpretations can be made. The pH is low and should be raised to near 5.8–6.0. At least some of the liming material should be dolomitic limestone to add Mg, which is in low to medium supply. Moderate amounts of K may or may not give an economic response. Sulfur and B are not part of the standard analysis package in Delaware, USA, because the amounts extracted by the standard Mehlich 3 procedure do not correlate well with plant uptake from soils. The P level is highly excessive, so P additions should be avoided, and steps taken to limit transport of P to waterways. As Delaware is in a humid region, N application is recommended based on yield goal and soil properties that affect mineralization, but not on an analytical test for available N. In a dry region, test labs would also measure nitrate and electrical conductivity in the soil to support recommendations concerning N fertilization and salt management, respectively.* (Soil test report courtesy of K. L. Gartley, University of Delaware)

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Merits of Soil Testing

It must not be inferred from the preceding discussion that the limitations of soil testing outweigh its advantages. When the precautions already described are observed, soil testing is an invaluable tool in making effective use of nutrients.

Soil Testing in Agriculture. These tests are most useful when they are correlated with the results of field fertilizer experiments (Figure 16.49). Adding amendments to achieve some "ideal" balance of nutrients in the soil is often wasteful of money and resources. Rather, soil tests used correctly in conjunction with calibration experiments can indicate what level of amendment needs to be added, if any, to allow the soil to supply sufficient nutrients for optimal plant growth (see also Section 15.2).

Dependability in predicting how plants will respond to soil amendments varies with the particular soil test, the tests for some parameters being much more reliable than others because of the consistency and breadth of field correlation data. In general, there are quite reliable tests for pH (need for liming or acidification), P, K, Mg, B, and Zn. Some soil test labs report additional soil properties such as other micronutrients (Cu, Mn, Fe, Mo, etc.), humus extractions (fulvic, humic, fractions, etc.), nonacid cation ("base") saturation, and even levels of soil respiration or various microbial populations (fungi, bacteria, nonparasitic nematodes, etc.). However, the basis for making valid and practical recommendations for managing soil fertility based on such soil test parameters is currently very scant, at best.

Testing in Forestry. Generally, soil testing has been most relied upon in agricultural systems, while foliar analysis has proved more widely useful in forestry. The limited use of soil

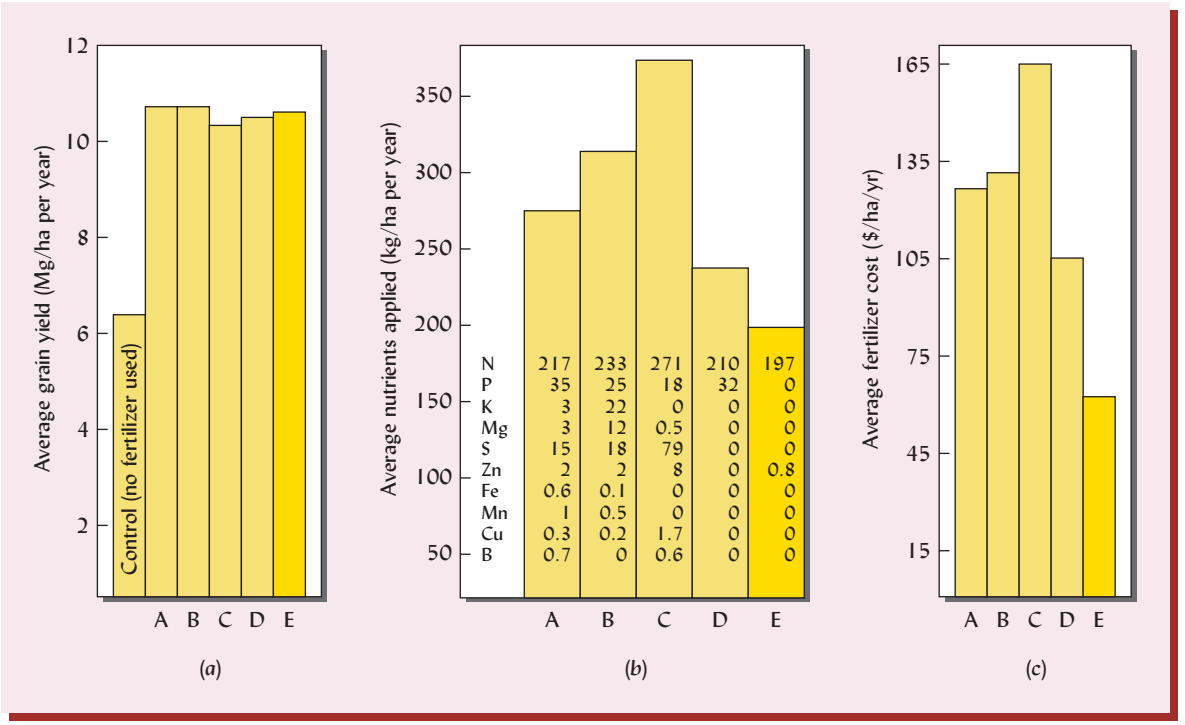

Figure 16.49 *(a) The yield of corn from plots near North Platte in Nebraska, USA, receiving fertilizers as recommended by five soil testing laboratories (A–E). (b) The nutrient additions recommended by these laboratories and (c) the annual cost of the recommended fertilizers. The yields from all fertilized plots were about the same, even though rates of fertilizer application differed markedly. The fertilizer rates recommended by laboratory E utilized a sufficiency-level concept that was based on the calibration of soil tests with crop yield responses in the field. Those recommended by laboratories A–D were based either on a maintenance concept that required replacement of all nutrients removed by a crop or on the supposed need to maintain certain cation ratios (Ca/Mg, Ca/K, and Mg/K). Obviously, the sufficiency-level concept was most economical. As a result of this and many other similar comparison studies, most university soil test labs have adopted the sufficiency-level approach. Data averaged over a six-year period. The soil was a Cozad silt loam (Fluventic Haplustoll).* [From Olson et al. (1982); used with permission of American Society of Agronomy]

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testing in forestry is partly due to the fact that trees, with their extensive perennial root systems, integrate nutrient bioavailability throughout the profile. This, combined with the typically complex nutrient stratification in forested soils, creates a great deal of uncertainty about how to obtain a representative sample of soil for analysis. In addition, because of the comparably long time frame in forestry, limited information is available on the correlation of soil test levels with timber yields in the sense that such information is widely available for agronomic crops (see Figure 16.47). An exception may be the conifer plantations on Ultisols of the southeastern United States, where the wood volume responses to P fertilization at various soil test levels have been studied extensively. Even though the relationship between tree growth and soil test level is not well known for most other forest systems, standard agronomic soil testing can still be useful in distinguishing those soils whose ability to supply P or K is adequate from those with very low supplying power for these nutrients.

16.12 SITE-INDEX APPROACH TO PHOSPHORUS MANAGEMENT

As concerns have increased about nonpoint source water pollution, research has identified phosphorus movement from land to water as a major cause of aquatic ecosystem degradation, especially for lakes. In most industrial countries, municipal sewage systems are *the* major point source of phosphorus water pollution and agricultural land is *the* major nonpoint source of phosphorus water pollution. Society continues to invest in upgrading sewage treatment facilities to reduce phosphorus loading from those sources. The situation demands that the amounts of phosphorus contributed from agricultural land also be drastically reduced in some areas.

Phosphorus movement from land to water is determined by *phosphorus-transport*, *phosphorus-source*, and *phosphorus-management* parameters. Transport parameters include the mechanisms that govern how rain, snowmelt, and irrigation water cause phosphorus to move across the landscape in runoff and sediment. Source parameters include the amount and forms of phosphorus on and in the soil. Management parameters include the method of application, timing, and placement of phosphorus and such disturbances as tillage.

Overenrichment of Soils

In Section 14.1 we learned how phosphorus, so scarce in nature, has accumulated over a period of decades to excessive levels in many agricultural soils as a result of two historical trends. In the case of phosphorus fertilizer, research in the early and mid-20th century suggested that farmers needed to add several times the amount of phosphorus that plants were likely to use, because soils were found to fix most of the added phosphorus in unavailable forms. Applications of 40–100 kg P/ha became standard practice, even though crop harvests removed only about one-third of that amount. The phosphorus not removed in harvest accumulated in the soil, and eventually satisfied a large fraction of the soil's phosphorus fixation capacity. It was not until the 1980s and 1990s that many farmers and researchers realized that soils with a long history of phosphorus fertilization were no longer in need of phosphorus application levels above what the crops would remove.

The second trend that contributed to the phosphorus pollution problem was the concentration of livestock and the subsequent heavy applications of animal manure to soils nearby (see Section 16.2). Much of the nitrogen added in the manure was lost to the environment by volatilization or leaching, but the phosphorus, being much less mobile, mostly remained in the soil. In recent years, farmers have begun to apply manure in amounts calculated to just meet the crop's nitrogen needs. Even so, the amount of phosphorus applied is still far more than plants can use (remember, from Section 16.6, that plants use about ten times as much nitrogen as phosphorus, but manures—especially if not handled carefully to avoid nitrogen losses—contain only one to four times as much nitrogen as phosphorus).

Because of these trends, some farm fields have become so high in phosphorus that rain or irrigation water interacting with the soil carries away enough phosphorus to impair the ecology of receiving waters. It is imperative that sites with such a high potential to cause phosphorus pollution be identified and appropriately managed to reduce their environmental impact. It may take decades to lower soil test P levels on these farms back to the optimum range (Figure 16.50) and phosphorus fertilizers are not likely to be needed on them for decades more.

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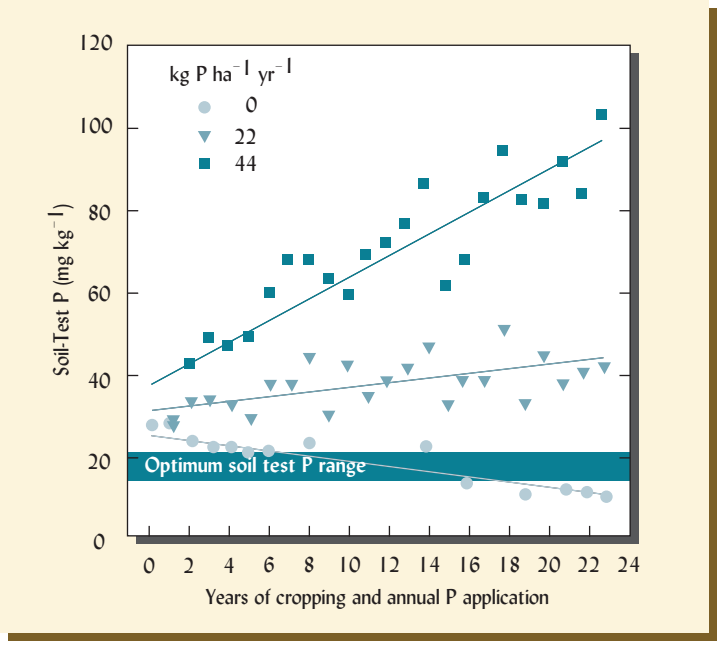

Figure 16.50 *Changes in soil test P as a result of annual applications of 0, 22, or 44 kg P ha^{-1} to a corn-soybean rotation on an Iowa Mollisol. Data from this and other sites in the study suggest that application of 12–20 kg P ha^{-1} yr^{-1} is sufficient to balance P removed in crop harvests and maintain soil test P in the optimal range for many cropping systems. The gentle slope of the zero P added line suggests that many decades of crop harvest removals would be needed to bring the most elevated P levels back to the optimum range. The soil tests were conducted using the Bray-1 method for which the optimal levels are 16–22 mg P extracted per kg soil.* [Data from Dodd and Mallarino (2005) with permission of the Soil Science Society of America]

Transport of Phosphorus from Land to Water

Two fundamental conditions must be met for a soil to cause significant phosphorus pollution. First, the supply of phosphorus in the soil must be relatively large; second, the characteristics of the site and soil must allow significant transport of phosphorus from the soil in the field to a receiving water body such as a lake or stream. A review of the phosphorus cycle (Section 14.3) reminds us that phosphorus can move from land to water by three principal pathways:

1. Attached to eroded soil particles (the main P-loss pathway from tilled soils).
2. Dissolved in water running off the surface of the land (a major pathway for pastures, woodland, and no-till cropland).
3. Dissolved or attached to suspended colloidal particles in water percolating down the profile and through the drainage pipes or groundwater aquifers that feed streams or lakes (a significant pathway in very sandy or poorly drained soils with shallow water tables and possibly in heavily manured soils with many continuous macropores).

Phosphorus Soil Test Level as Indicator of Potential Losses

Phosphorus in Eroded Sediment. Phosphorus attached to eroded soil particles accounts for the greatest amount of phosphorus contributed to receiving waters from most agricultural landscapes. As discussed in Section 14.2, the eroded fraction is usually more concentrated in phosphorus than the soil left behind. While phosphorus strongly adsorbed onto mineral particles may not be as available to aquatic phytoplankton and algae as that carried in solution, such sediments tend to accumulate on lake and river bottoms, where their phosphorus becomes increasingly soluble because of iron reduction reactions. Soils that are both highly erodible and highly enriched with phosphorus (as indicated by excessive phosphorus soil test levels) represent the most serious potential for phosphorus pollution.

Phosphorus in Runoff Water. As described in Section 16.11, soil testing was designed to determine how well a soil can supply nutrients to plant roots. However, routinely used phosphorus soil tests have been shown to also provide a useful (though not perfect) indication of how readily phosphorus will desorb from a soil and dissolve in runoff water. The relationship between phosphorus soil test level in the upper centimeter or two of soil and phosphorus in runoff water is not linear (Figure 16.51). Rather, the relationship exhibits a threshold effect such that little phosphorus is lost to runoff if soils are near or below the optimal range for

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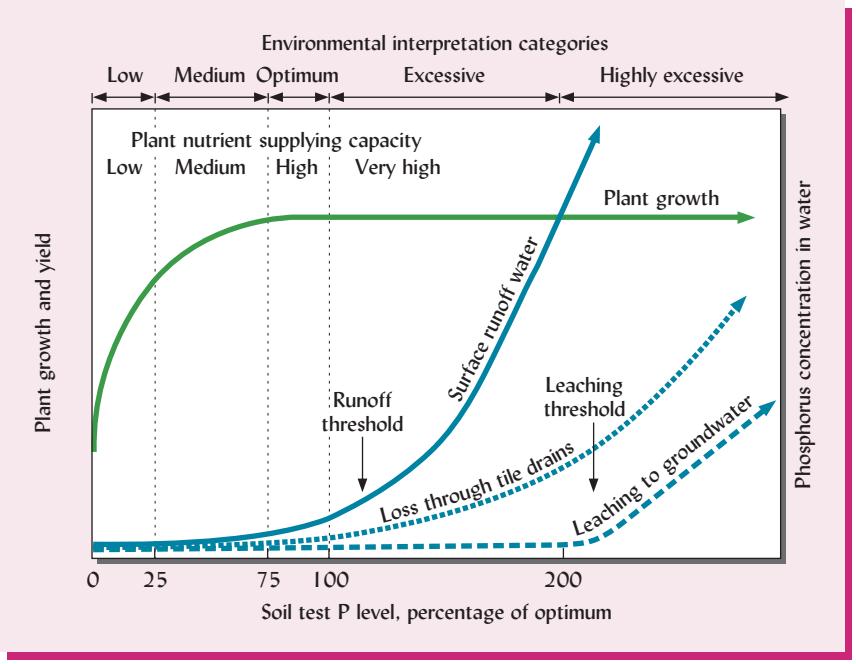

Figure 16.51 *A generalized relationship between soil test P levels and environmental losses of P dissolved in surface runoff and subsurface drainage waters. The relationship between traditional plant nutrient supply interpretation categories and environmental interpretation categories is also indicated. The diagram suggests that, fortunately, soil P levels can be achieved that are both conducive to optimum plant growth and protective of the environment. If P losses by soil erosion are controlled (although not shown, this is a big if), significant quantities of dissolved P would be lost only when soils contain P levels in excess of those needed for optimum plant growth. Losses of P by leaching in drainage water are significant only at very high soil P levels, as this pathway rapidly increases only after the P-sorption capacity of the soil is substantially saturated. As indicated by the dotted curve, short-circuiting this pathway by installing tile drainage is likely to lower the threshold for subsurface leaching P loss. The vertical axes are not to scale.* [Figure courtesy of Ray R. Weil, based on concepts discussed in Sharpley (1997), Higgs et al. (2000), and Reid et al. (2012)]

plant growth, but the amount released from the soil to runoff water increases exponentially as phosphorus soil test levels rise much higher than this. Therefore, as suggested by Figure 16.51, it appears that soils can be maintained at phosphorus levels sufficient for optimal plant growth without undue losses of phosphorus in runoff water. As is also the case with nitrogen, significant environmental damages are associated with excess—the application of more nutrient than is really needed. Therefore, an environmentally sound phosphorus fertility level, and one that also conserves the world's finite stocks of this essential element, should also be a profitable level of fertilization.

Phosphorus in Drainage Water. Drainage water from most soils is usually very low in phosphorus because as phosphorus-laden water percolates from the surface down through the subsurface soil horizons, dissolved $H_2PO_4^-$ is strongly sorbed by inner-sphere complexation onto Fe-, Al-, Mn-, and Ca-containing mineral surfaces (Sections 8.7 and 14.8). However, under certain circumstances this mechanism is not so effective in removing phosphorus from drainage water. These circumstances include the following:

1. The percolating water is flowing through macropores and has little contact with soil surfaces (Section 6.8). This may occur under long-term no-till management or in pastures, especially if installation of tile drainage (see Section 6.7) has shortened the flow pathways and increased the opportunities for P loss by preferential flow output.
2. The dissolved phosphorus is not in mineral ($H_2PO_4^-$ or HPO_4^{2-}) forms, but instead is part of soluble organic molecules, which are not strongly sorbed by mineral surfaces. This situation is common under forests or heavily manured soils.
3. The phosphorus is sorbed onto the surface of dispersed colloidal particles that are so small that they remain suspended in the percolating water.
4. The phosphorus-fixation capacity of the soil is so small (as in sands, Histosols, and some waterlogged soils with reduced iron) or already so saturated with phosphorus (as in soils overloaded with phosphorus after many years of excessive manure and fertilizer applications) that little more phosphorus can be sorbed (see Figure 16.51).

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Site Characteristics Influencing Transport of Phosphorus

To cause environmental damage, the phosphorus-rich sites must also have characteristics conducive to the transport of phosphorus to sensitive bodies of water. Such characteristics might include close proximity to the water body, the absence of a protective vegetated buffer, erodible soils, or high runoff rates caused by low permeability and steep slopes. Control of soil erosion by conservation tillage, mulches, and other practices discussed in Chapter 17 can greatly reduce the transport of sediment-associated phosphorus, but will have little effect on, or may even increase, the loss of phosphorus dissolved in runoff or drainage water. In fact, when no-till fields are fertilized, the phosphorus tends to accumulate in the upper 1–2 cm of soil, where it is most susceptible to desorption into runoff water. The beneficial influence of buffers in removing both dissolved and sediment-associated phosphorus from runoff was discussed in Section 16.2.

Phosphorus Site Index

In order to focus control measures on the sites within a watershed that account for most of the phosphorus loss, each field can be evaluated using an index of phosphorus pollution risk. Commonly referred to as a *phosphorus site index* (Table 16.16), such a tool integrates phosphorus source, transport, and management characteristics of a site into a single number. Box 16.4 illustrates how such an index can be calculated for a specific farm field (or a separately identified part of a field). Analysis of the individual index parameters should indicate which ones most influenced the index. One can then develop plans for corrective action to address problems associated with these identified parameters. An important part of such plans is the restriction of further phosphorus application, whether in manure or fertilizer (Table 16.17).

16.13 SOME ADVANCES AND CHALLENGES IN FERTILIZER MANAGEMENT

The initial focus in most soil fertility plans is on nitrogen, the nutrient to which nonleguminous plants most commonly and most dramatically respond. Nitrogen is also at the forefront because of its implications for environmental quality. Applications of other nutrients are usually made to balance and supplement the nitrogen supply whether that comes from soil organic matter, crop residues, organic wastes, or organic and inorganic fertilizers. Nonetheless, we must be mindful that the effectiveness of nitrogen applications can be limited by deficiencies of sulfur, potassium, phosphorus, or other nutrients. Assuming other nutrients are well-supplied, and the required amount of nitrogen to supply is usually at least enough to replace that removed in the harvested product at a realistically expected yield level.

Nitrogen Credits and Predictions. This estimated fertilizer rate should be adjusted by the amount of any additional gains or losses not taken into account in the standard response curve. For example, nitrogen contributions from previous or current manure applications (see Box 16.2), legume cover crop (see Figure 13.40), previous legume in the rotation (see Figure 13.35), or nitrate in irrigation water should be subtracted from the amount of fertilizer recommended.

In arid and semiarid regions where overwinter leaching is minimal, the nitrate nitrogen found in the upper 60–120 cm of the profile in spring is often used along with data on soil organic matter levels to estimate the nitrogen that will be available. In humid regions the soil nitrate-N concentration in the upper 30 cm of soil just before side-dressing time (the PSNT, see Section 16.11) is used to predict nitrogen mineralization levels for the growing season. Several chemical soil tests are also being developed to help predict the amount of nitrogen that will be mineralized from a particular soil during a particular growing season.

Plant Response. We can analyze the soil to estimate its nutrient supplying power and we can calculate the amount of each nutrient removed from the field by harvests, but the response of growing plant is the final arbitrator of soil fertility management. The soil–plant–weather systems that govern plant growth and crop yield are so highly complex and variable that we are challenged to be able to predict exactly what nutrient management will be optimal. Even with

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Table 16.16

PHOSPHORUS SITE INDEX BASED ON SITE CHARACTERISTICS THAT AFFECT THE AVAILABILITY OF PHOSPHORUS AT THE SOURCE AND THE TRANSPORT OF PHOSPHORUS TO SENSITIVE RECEIVING WATERS[a]

This example illustrates the types of parameters and relationships among parameters that might be used to rank individual farm fields or parts of fields as potential sources of phosphorus pollution. In adapting this type of phosphorus index tool, the site and management characteristics included, the weights used for each, and the method of calculation should reflect local conditions.

		Phosphorus loss rating (B)					
Parameter	**Weight factor (A)**	**None 0**	**Low 1**	**Medium 2**	**High 4**	**Very high 8**	**Score (A × B)**
P transport characteristics							
1. Annual soil erosion by rain[b]	1.5	<2	2–8	8–12	12–32	>32	_____
2. Erosion by irrigation water	1.0	Not irrigated	Tailwater return or no visible runoff	*QS*[c] >38 for erosion-resistant soils	*QS* >38 for erodible soils or visible runoff at field border	*QS* >38 for very erodible soils or rills visible	_____
3. Runoff class[d]	1	Very low	Low	Medium	High	Very high	_____
4. Distance from field edge to lake or stream	1	>30 m	15–30 m	8–15 m	4–8 m	<4 m	_____
5. Vegetated buffer between field and lake or stream[e]	0.5	>30 m	15–30 m	8–15 m	4–8 m	<4 m	_____
6. No P application zone (above any vegetated buffer)	0.5	>15 m	10–15 m	5–10 m	2–5 m	<2 m	_____
7. Receiving water priority rating[f]	1	Very low	Low	Medium	High	Very high	_____
Score 1 + score 2 + … + score 7 = total score for P transport→							
P source characteristics							
1. Soil test P category where >100 is considered excessive[g]	1	Low 0–25	Medium 26–75	Optimum 76–100	Excessive 101–200	Highly excessive >201	_____
2. P fertilizer application rate, kg P/ha	0.75	None	1–15	16–45	46–75	>75	_____
3. P fertilizer application method	0.5	None applied	Inject or band deeper than 5 cm	Incorporate within 5 days of application	Surface apply in summer or incorporate after >5 days	Surface apply during winter and not incorporate	_____
4. Organic P source application rate, kg P/ha[h]	1.0	None	1–15	16–30	31–45	>46	_____
5. Organic P source application method	1.0	None applied	Inject or band deeper than 5 cm	Incorporate within 5 days of application	Surface apply in summer or incorporate after >5 days	Surface apply during winter and not incorporate	_____
Score 1 + score 2 + … + score 5 = total score for P source→							_____
(P transport score) × (P source score) = combined P site index for risk of water pollution→							_____
Combined P site index:	0–10	11–50	51–250	251–1000	>1000		_____
Risk of P pollution:	Negligible	Low	Medium	High	Very high		_____

[a]Adapted from models and concepts discussed in USDA/NRCS (2007), Gburek et al. (2000),and Snyder et al. (2005). In any given region, the appropriate phosphorus index matrix table would differ somewhat from the general model shown here.

[b]Mg/ha as determined by RUSLE—see Section 17.4.

[c]Q = flow rate (L/min) of water applied to a furrow; S = slope (%). $Q \times S = QS$.

[d]Ranging from permeable soils on nearly level sites (none) to impermeable soils on slopes >20% (very high).

[e]See Section 16.2. Perennial grass nearest the field combined with forest vegetation nearest the stream is ideal.

[f]Not all areas have official priority rankings. Low priority would typically be an already-polluted artificial holding pond, while highest priority would be a pristine lake very sensitive to eutrophication.

[g]Not all soil test reports give results on this scale. "Excessive" may be termed "very high" by some labs (see Figure 16.48).

[h]The P from an organic source may be multiplied by an availability factor to estimate the fraction of total P in an organic material that will be released in a year.

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BOX 16.4

HOW A PHOSPHORUS SITE INDEX WORKS

The phosphorus site index in Table 16.16 assigns a rating of 0–8 for different degrees of risk from each phosphorus source parameter and phosphorus transport parameter. The weights listed in the second column represent professional judgments as to how much each parameter is likely to influence phosphorus pollution. The weight multiplied by the rating gives a partial score for each parameter. These partial scores are then added together to give two total scores, one for phosphorus source and one for phosphorus transport. The product obtained by multiplying these two scores yields an overall combined score that indicates in which of five categories of risk the site belongs. Consider the following example:

A particular field is located only 12 m from the edge of a sensitive lake (priority = high) and there is no zone left at the field edge without phosphorus application. The field is bordered by a 12-m-wide vegetated buffer strip. The field is not irrigated and is moderately erodible (10 Mg/ha estimated annual erosion). The runoff class is medium because although the soil is moderately permeable, the site is steeply sloping. The upper layer of soil tests in the highly excessive range (300) because of a long history of phosphorus applications. No inorganic phosphorus fertilizer is now applied, but plans are to surface-apply, in winter, enough liquid manure to supply about 40 kg P/ha. The parameter scores in Table 16.16 are calculated here. For example, for the first parameter, the weight factor from Table 16.16 is 1.5 and the rating is 2, so $1.5 \times 2 = 3.0$, the partial score for this parameter.

Transport Parameter	Calculations (source parameters)	Partial score	P source parameter	Calculations (transport parameters)	Partial score
1	$1.5 \times 2 =$	3.0	1	$1.0 \times 8 =$	8.0
2	$1.0 \times 0 =$	0.0	2	$0.75 \times 0 =$	0
3	$1.0 \times 2 =$	2.0	3	$0.5 \times 0 =$	0
4	$1.0 \times 2 =$	2.0	4	$1.0 \times 4 =$	4.0
5	$0.5 \times 2 =$	1.0	5	$1.0 \times 8 =$	8.0
6	$0.5 \times 8 =$	4.0	Total P source score		20.0
7	$1.0 \times 4 =$	4.0			
Total P transport score		16.0			
Combined P pollution risk index: $16 \times 20 = 320$, indicates high risk					

Based on the combined score of 320, this site has a high risk for phosphorus movement from the site (see rating chart at bottom of Table 16.16). There is a high probability for an adverse impact to surface-water resources unless remedial action is taken. Soil and water conservation as well as phosphorus management practices are necessary to reduce the risk of phosphorus movement and probable water-quality degradation. The partial scores suggest that the situation could be corrected by addressing transport parameter 6 (create a no-phosphorus application zone along the lower edge of the field), source parameter 4 (reduce the amount of organic nutrient source applied), and source parameter 5 (incorporate the organic nutrient source rather than applying it to the surface in winter). Transport parameter 7 (the priority ranking of the receiving water) and source parameter 1 (the current phosphorus soil test level) also contribute substantially to the combined index, but these factors are not subject to management change.

all the advances in sensing, analysis, and computer modeling of these systems, we still must rely on well-designed field experiments to define the relationships between the addition of nutrients and the resulting plant growth or crop yield responses. The optimal level of nitrogen fertilization is usually determined by the shape of such response curves (Figure 16.52).

Profitability. A second aspect relates to economics. Farmers do not use fertilizers just to grow big crops or to increase the nutrient content of their soils. They do so to make a living. The most profitable rate is determined by the ratio of the value of the extra yield expected to the cost of the fertilizer applied. The law of diminishing returns applies. Therefore, the most profitable fertilizer rate will be somewhat less than the rate that would produce the very highest yield (Figure 16.52).

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Table 16.17
PHOSPHORUS APPLICATION IN ACCORDANCE WITH VARIOUS MEASURES OF WATER POLLUTION RISK
The guidelines given here are generalized from USDA/NRCS national guidelines and should be modified as needed according to local soil, water, and agricultural conditions.

Determine one of these measures of soil P status			Suitable application rates of P from organic or inorganic P sources	
Soil test P level[a]	Soil test P relative to runoff loss threshold[b]	Site index for risk of P pollution[c]	Organic nutrient source[d]	Inorganic P fertilizer
Low	<0.75 × threshold	Low	To supply needed N	20–50 kg/ha
Medium	<0.75 × threshold	Medium	To supply needed N	15–30 kg/ha
High	0.75 to 1.5 × threshold	Medium–high	To supply only the P in harvested crop	0–20 kg/ha
Very high (excessive)	1.5 to 2.0 × threshold	High	To supply $^1/_2$ the P in harvested crop	0–10 kg/ha starter only
Highly excessive	>2 × threshold	Very high	No P application	

[a]Interpretive levels based on the high category being sufficient for optimum plant production. See Section 16.11.
[b]For use when soil-specific phosphorus threshold values are available for the soils in question. See Figure 16.51 for an illustration of this concept.
[c]An index that integrates soil, landscape, and water resource characteristics such as Table 16.16.
[d]Such as manure, sewage sludge, compost, etc. If these materials are applied at rates to meet N needs, P will accumulate and eventually move the site into a higher soil P status category.

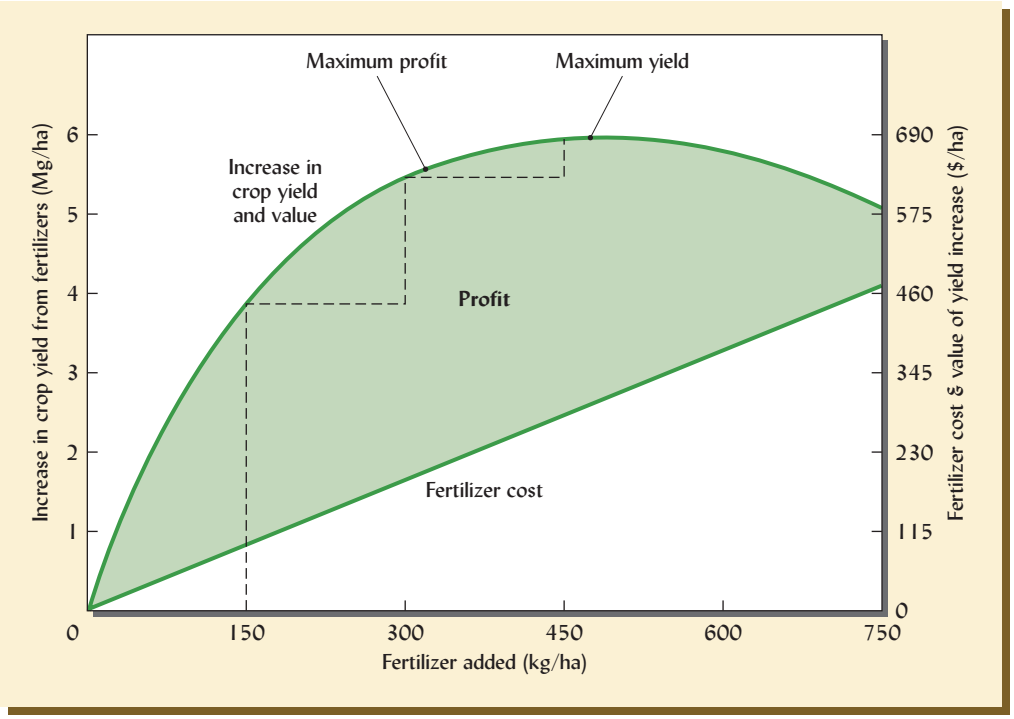

Figure 16.52 *Relationships among the rate of fertilizer addition, crop yield increase, fertilizer costs, and profit from adding the fertilizer. Note that the yield increase (and profit) from the first 150 kg of fertilizer is much greater than from the second and third 150 kg. Also note that the maximum profit is obtained at a lower fertilizer rate than that needed to give a maximum yield. The calculations assume that the yield response to added fertilizer takes the form of a quadratic curve, an assumption which often leads to overestimating fertilizer rates needed to optimize profit.*

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Response Curves. Traditionally, economic analysis of optimum fertilizer rates has assumed that the plant response to fertilizer inputs was represented by a smooth curve following a quadratic function ($y = a + bx + cx^2$). In fact, actual data obtained can be just as well described by a number of other mathematical functions (Figure 16.53). This seemingly esoteric observation can have a great effect on the amount of fertilizer recommended and, in turn, on the likelihood of environmental harm from excessive fertilizer use (Figure 16.54). Among the various models studied, the linear-plateau approach (Figure 16.53*a*) usually leads to the lowest fertilizer recommendation, least wasted fertilizer, least environmental damage, and often the greatest profit as well.

Generally, these field studies are carried out on a variety of soils and under a range of different weather conditions. Differing weather patterns (a cold or warm spring, a dry or wet summer) cause the response to nitrogen and other nutrients to vary greatly from one year to the next, even in the exact same soil and location (Figure 16.54). The uncertainties related to nitrogen supply are still sufficiently high, and the cost of nitrogen fertilizer may be sufficiently low, that farmers tend to err on the side of oversupply, just for "insurance." In most years, this philosophy can be disadvantageous to both the farmer and the environment.

Weather patterns during the growing season influence the amount of N fertilizer needed in a given year. Both plant growth potential and soil N supply are highly susceptible to the influence of weather. If temperatures are not too cold or too hot, and rain falls when needed, plant growth and yield potentials will be high and will call for high amount of N. The weather also influences soil nitrogen processes such as mineralization, denitrification, and leaching. For instance, cool temperatures may slow mineralization and heavy rains may increase the loss of what N was mineralized. The PSNT makes a prediction of soil N availability based on a single actual data point for soil nitrate a week or so before sidedress time. Complex computer models may be able to make more accurate predictions of N supply and plant N demand by integrating large amounts of weather data with information about plant and soil processes (Figure 16.55). Another advantage of the computer models is that they can be updated throughout the season.

In Chapter 13 (Section 13.15) we discussed several technologies that help improve the management of nitrogen fertilizers. Many of these techniques have been adopted by farmers in recent years, including improved fertilizers, improved means of accounting for weather, and more careful management that produces more yield with less fertilizer. Fertilizer use and corn yield data for the United States (Figure 16.56) suggest that N fertilizer was not always used very efficiently, much to the detriment of both water quality and farmer profitably. Although some advisors continue to recommend as much as 27 kg N per Mg (1.5 lbs of N/bushel) of expected corn grain, most field data suggest that as little as 14–16 kg N/ Mg grain (0.8 or 0.9 lbs N/bushel) is all that is really required. Data indicate that fertilizers are

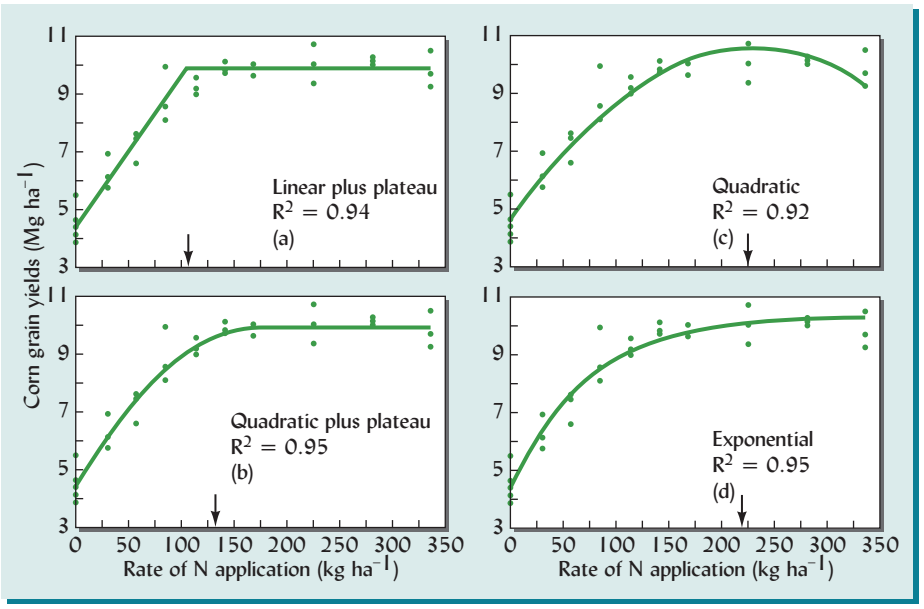

Figure 16.53 *The mathematical function chosen to represent fertilizer-response data can affect the amount of fertilizer recommended. The data in all four graphs are exactly the same and represent the response of corn yields in Iowa to increasing levels of nitrogen fertilization. The vertical arrows indicate the recommended, most profitable rate of nitrogen to apply according to each mathematical model. Note that all models fit the data equally well (as indicated by the very similar R^2 values), but that the* linear-plus-plateau *model predicts an optimum nitrogen rate of 104 kg/ha, while the commonly used* quadratic *model suggests that 222 kg/ha is the optimum. The extra 118 kg/ha of nitrogen would probably have no effect on crop yield, but could cost the farmer and greatly increase the risk of environmental damage.* [Redrawn from Cerrato and Blackmer (1990)]

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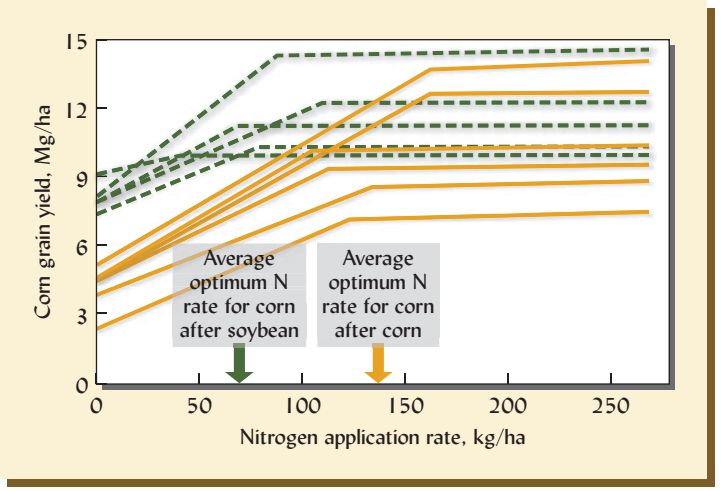

Figure 16.54 *Corn yield response to applied nitrogen in a single field can vary greatly depending on the weather and the previous crop grown. Each curve is of the linear-plateau type illustrated in Figure 16.53a and represents a different year with different weather. The green dashed curves represent corn after soybean and the yellow solid curves represent corn after corn. In the same field, the optimal rate of N ranged from as low as 60 to as high as 160 kg N/ha, with rotation corn always requiring less N than continuous corn.* [Graphed from selected data in Sawyer et al. (2006)]

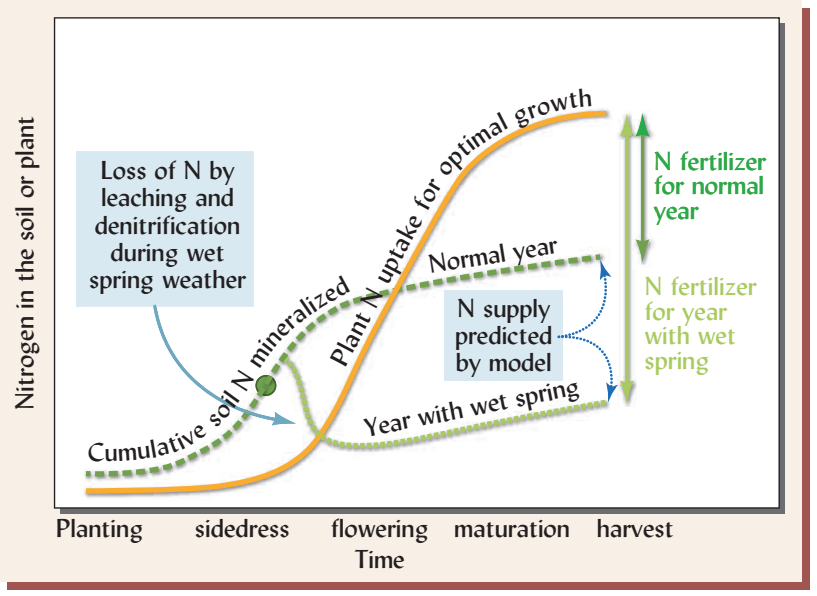

Figure 16.55 *Weather patterns during the growing season influence the amount of N fertilizer needed in a given year. Advanced, weather-driven computer models can help predict the most economic N rate to apply for a particular soil and weather combination. Compare to Figure 13.33 which illustrates two management approaches for N application to corn.* [Diagram based on concepts in Moebius-Clune et al. (2014)]

being used in advanced and emerging economies at greater than optimal rates. In the United States (Table 16.18) N and P balances are both positive, suggesting over application to soils already quite high in these nutrients. The water quality problems resulting from these over-applications are a continuing challenge. Even potassium, with a small negative balance in the United States, may be over applied if the potassium supplying capacity of the huge reserve in soil minerals is taken into consideration.

Anyone involved with the actual production of plants can testify to the enormous improvements that accrue from judicious use of organic and inorganic nutrient supplements. The preceding discussion suggests that while use of such supplements is often necessary, optimizing their management presents ongoing economic, resource, and environmental challenges.

16.14 CONCLUSION

The continuous availability of plant nutrients is critical for the sustainability of most ecosystems. The challenge of nutrient management is threefold: (1) to provide adequate nutrients for plants in the system; (2) to simultaneously ensure that inputs are in balance with plant utilization of nutrients, thereby conserving nutrient resources; and (3) to prevent contamination of the environment with unutilized nutrients.

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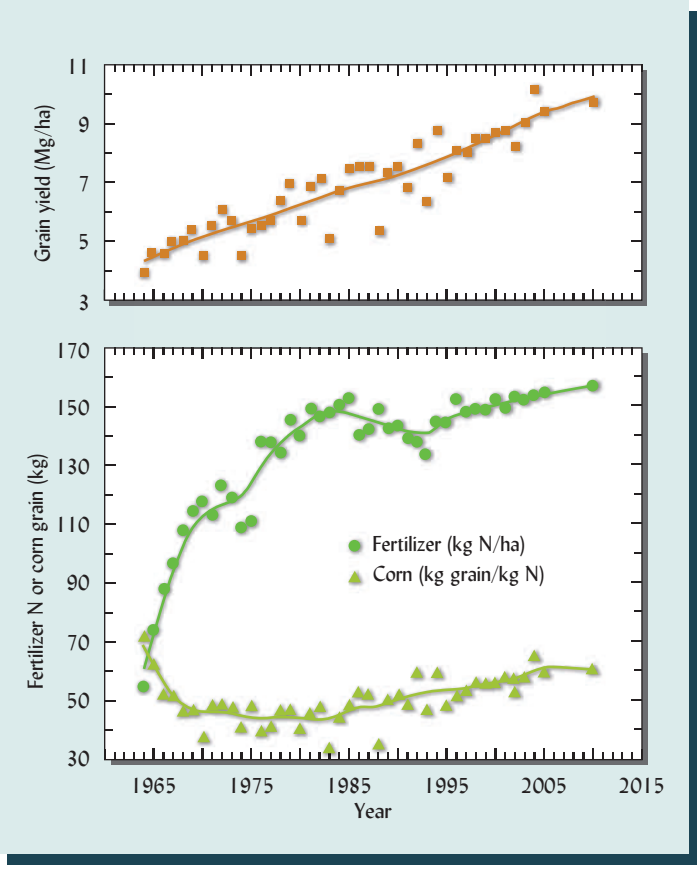

Figure 16.56 *Trends in U.S. corn grain yields (kg/ha, upper curve, squares), fertilizer N rate used for corn (kg N/ha, lower, circles), and resulting N use efficiency (lower, triangles). Nitrogen-use efficiency, defined as kg corn grain produced per kg N applied, declined during the 1960s and early 1970s when energy and N fertilizer were cheap. That is, even though corn yields were increasing, fertilizer use rate was increasing faster, so more and more N was being used to grow each kg of grain. Corn yields continued to rise steadily (due to more productive corn varieties and better soil management) from the mid-1980s to the mid-1990s, despite the fact that the average rate of fertilizer N application declined from 150 to 130 kg/ha during the same ten-year period. The lower fertilizer rates were encouraged by rising energy and fertilizer costs, and increasing environmental concerns. Efficiency continued to rise after the mid-1990s, as grain yield increases outpaced a slight rise in fertilizer rates. Future data will tell whether improvements in soil and water management and corn gemetics will continue to allow greater yields with little or no increase in N fertilizer.* [Data from USDA National Agricultural Statistics Service]

Table 16.18
NUTRIENTS REMOVED BY CROP HARVESTS IN THE UNITED STATES COMPARED TO NUTRIENTS APPLIED TO CROPLAND SOILS AS FERTILIZER, MANURE, OR FIXATION BY LEGUMES

On average more N and P are applied to croplands than the harvested crops remove, resulting in a surplus, part of which is susceptible to polluting waterways. In contrast, for K the data indicate a deficit, with more K being removed annually than is applied. Whether this deficit is made up for by release of K from soil minerals is a matter of some controversy. These are average values for the entire United States, so the balance for any single field or region may be quite different.

		N	P	K
		Millions of metric tons		
Sources applied	Fertilizer	11.4	1.8	3.6
	Legumes	6.0	0.0	0.0
	Manure	1.3	0.7	1.5
Total applied		18.7	2.5	5.1
Removed in harvest		13.6	2.2	6.5
Balance (surplus or deficit)		**+5.1**	**+0.3**	**−1.4**

Data are for years 2006–2008 from graphs in CAST (2013).

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The recycling of plant nutrients must receive primary attention in any ecologically sound management system. This can be accomplished in part by returning plant residues to the soil. These residues can be supplemented by judicious application of the organic wastes that are produced in abundance by municipal, industrial, and agricultural operations worldwide. The use of cover crops grown specifically to be returned to the soil is an additional organic means of recycling nutrients.

For sites from which crops or forest products are removed, nutrient losses commonly exceed the inputs from recycling. Inorganic fertilizers will continue to supplement natural and managed recycling to replace these losses and to increase the level of soil fertility so as to enable humankind to not only survive, but to flourish on this planet. In extensive areas of the world, fertilizer use will have to be increased above current levels to avoid soil and ecosystem degradation, to remediate degraded soils, and to enable profitable production of food and fiber.

The use of fertilizers, both inorganic and organic, should not be done in a simply habitual manner or for so-called insurance purposes. Rather, soil testing and other diagnostic tools should be used to determine the true need for added nutrients. In managing nitrogen and phosphorus, increasing attention will have to be paid to the potential for transport of these nutrients from soils where they are applied to waterways where they can become pollutants. If soils are low in available nutrients, fertilizers often return several dollars' worth of improved yield for every dollar invested. However, where the nutrient-supplying power of the soil is already sufficient, adding fertilizers is likely to be damaging both to the bottom line and to the environment.

STUDY QUESTIONS

1. The groundwater under a heavily manured field is high in nitrates, but by the time it reaches a stream bordering the field, the nitrate concentration has declined to acceptable levels. What are likely explanations for the reduction in nitrate?
2. You want to plant a cover crop in fall to minimize nitrate leaching after the harvest of your corn crop. What characteristics would you look for in choosing a cover crop to ameliorate this situation?
3. What management practices on forested sites can lead to significant nitrogen losses, and how can the losses be prevented?
4. What effect do forest fires have on nutrient availabilities and losses to streams?
5. Compare the resource-conservation and environmental-quality issues related to each of the three so-called fertilizer elements, N, P, and K.
6. A park manager wants to fertilize an area of turfgrass with nitrogen and phosphorus at the rates of 60 kg/ha of N and 20 kg/ha of P. He has stocks of two types of fertilizers: urea (45-0-0) and diammonium phosphate (18-46-0). How much of each should he blend together to fertilize a 10-ha area of turfgrass?
7. How much phosphorus (P) is there in a 25-kg bag of fertilizer labeled "20-20-10"?
8. Compare the relative advantages and disadvantages of organic and inorganic nutrient sources.
9. A certified organic grower plans to grow a crop that requires the application of 120 kg of plant-available N/ha and 20 kg/ha of P. She has a source of compost that contains 1.5% total N (with 10% of this available in the first year) and 1.1% total P (with 80% of this available in the first year). (a) Assuming her soil has a low P soil test level, how much compost should she apply to provide the needed N and P? (b) If her soil is already optimal in P, how can she provide the needed amounts of both N and P *without* causing further P buildup?
10. Discuss the concept of the *limiting factor* and indicate its importance in enhancing or constraining plant growth.
11. Consider Figure 16.37, which illustrates the response of wheat plants (shoot weight) to increasing soil P, Zn, and bulk density. (a) Explain, using specific data, how the graphs illustrate the principle of limiting factors (or "the law of the minimum"). (b) Describe the conditions in the experiment under which compaction (rather than zinc or phosphorus) is the most limiting factor. (c) Explain in detail, using specific data, how the graphs also illustrate exceptions to or limitations of the "law of the minimum."
12. Why are nutrient-cycling problems in agricultural systems more prominent than those in forested areas?
13. Discuss how GIS-based, site-specific nutrient-application technology might improve profitability and reduce environmental degradation.
14. Discuss the value and limitations of soil tests as indicators of plant nutrient needs and water pollution risks.
15. When might the use of plant tissue analyses have advantages over soil testing for correcting nutrient imbalances?

FOR REFERENCE PURPOSES ONLY

REFERENCES

Aber, J., et al. 2000. "Applying ecological principles to management of the U.S. National Forests." *Issues in Ecology*, 6. Ecological Society of America, Washington, D.C. www.esa.org/science_resources/Issues/FileEnglish/Issues6.pdf (confirmed 12 September 2006).

Barzegar, A. R., H. Nadian, F. Heidari, S. J. Herbert, and A. M. Hashemi. 2006. "Interaction of soil compaction, phosphorus and zinc on clover growth and accumulation of phosphorus." *Soil Tillage Research* **87**:155–162.

Beegle, D. B., L. E. Lanyon, and J. T. Sims. 2002. "Nutrient balances." In P. M. Haygarth and S. C. Jarvis (eds.). *Agriculture, Hydrology and Water Quality*. CAB International, Wallingford, UK, pp. 171–193.

Billen, G., J. Garnier, and L. Lassaletta. 2013. "The nitrogen cascade from agricultural soils to the sea: Modelling nitrogen transfers at regional watershed and global scales." *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**: 20130123..

Binkley, D., H. Burnham, and H. L. Allen. 1999. "Water quality impacts of forest fertilization with nitrogen and phosphorus." *Forest Ecology and Management* **121**:191–213.

Bormann, F. H., and G. E. Likens. 1979. *Pattern and Process in a Forested Ecosystem*. Springer-Verlag, New York.

Bouwman, L., K. K. Goldewijk, K. W. Van Der Hoek, A. H. Beusen, D. P. Van Vuuren, J. Willems, M. C. Rufino, and E. Stehfest. 2013. "Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900– 2050 period." *Proceedings of the National Academy of Sciences* **110**:20882–20887.

Brown, T. C., and D. Binkley. 1994. "Effect of management on water quality in North American forests." USDA Forest Service General Technical Report RM-248, USDA, Fort Collins, CO.

CAST. 2013. "Food, fuel, and plant nutrient use in the future," Issue Paper 51. Council for Agricultural Science and Technology (CAST), Ames, IA. http://www.cast-science.org/download.cfm?PublicationID=271532&File=1e306e163f98d5ad8b693f41b1d755f4a382TR.

Cerrato, M. E., and A. M. Blackmer. 1990. "Comparison of models from describing corn yield response to nitrogen fertilizer." *Agronomy Journal* **98**:138–143.

Dean, J. E., and R. R. Weil. 2009. "Brassica cover crops for nitrogen retention in the mid-Atlantic coastal plain." *Journal of Environmental Quality* **38**:520–528.

Dodd, J. R., and A. P. Mallarino. 2005. "Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn-soybean rotations." *Soil Science Society of America Journal* **69**:1118–1128.

FAO. 1977. *China: Recycling of Organic Wastes in Agriculture*. FAO Soils Bulletin 40. U.N. Food and Agriculture Organization, Rome.

FAO. 2014. FAOSTAT [Online]. Food and Agriculture Organization of the United Nations. Available at http://faostat.fao.org/ (verified 20 May 2014).

Fernandez-Martinez, M., S. Vicca, I. A. Janssens, J. Sardans, S. Luyssaert, M. Campioli, F. S. Chapin III, P. Ciais, Y. Malhi, M. Obersteiner, D. Papale, S. L. Piao, M. Reichstein, F. Roda, and J. Penuelas. 2014. "Nutrient availability as the key regulator of global forest carbon balance." *Nature Climate Change* **4**:471–476.

Fisher, J. B., G. Badgley, and E. Blyth. 2012. "Global nutrient limitation in terrestrial vegetation." *Global Biogeochemical Cycles* **26**:GB3007.

Gardner, G. 1997. *Recycling Organic Waste: From Urban Pollutant to Farm Resource*. Worldwatch Paper 135. Worldwatch Institute, Washington, D.C.

Gburek, W. J., A. N. Sharpley, L. Heatherwaite, and G. J. Folmar. 2000. "Phosphorus management at the watershed scale: A modification of the phosphorus index." *Journal of Environmental Quality* **29**:130–144.

Haering, K. C., W. L. Daniels, and S. E. Feagley. 2000. "Reclaiming mined lands with biosolids, manures and papermill sludges." In R. I. Barnhisel, W. L. Daniels, and R. G. Darmody (eds.). *Reclamation of Drastically Disturbed Lands*, Agronomy Monograph 41. American Society of Agronomy, Madison, WI, pp. 615–644, Chapter 24.

Havlin, J. L., T. S. L., W. L. Nelson, and J. D. Beaton. 2014. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*, 8th ed. Pearson, Upper Saddle River, NJ, p. 528.

He, X.-T., T. Logan, and S. Traina. 1995. "Physical and chemical characteristics of selected U. S. municipal solid waste composts." *Journal of Environmental Quality* **24**:543–552.

Heckman, J. R., and D. Kluchinski. 1996. "Chemical composition of municipal leaf waste and hand-collected urban leaf litter." *Journal of Environmental Quality* **25**:355–362.

Higgs, B., A. E. Johnston, J. L. Salter, and C. J. Dawson. 2000. "Some aspects of achieving sustainable phosphorus use in agriculture." *Journal of Environmental Quality* **29**:80–87.

Hilimire, K. 2011. "Integrated crop/livestock agriculture in the United States: A review." *Journal of Sustainable Agriculture* **35**:376–393.

Hochmuth, G., D. Maynard, C. Vavrina, E. Hanlon, and E. Simonne. 2012. "Plant tissue analysis and interpretation for vegetable crops in Florida," *Horticulture Science Extension HS964*. University of Florida. http://edis.ifas.ufl.edu/ep081.

Jones Jr., J. B. 2012. *Plant Nutrition and Soil Fertility Manual*. CRC Press, Boca Raton, FL, p. 285.

Kröger, R., E. Dunne, J. Novak, K. King, E. McLellan, D. Smith, J. Strock, K. Boomer, M. Tomer, and G. Noe.

FOR REFERENCE PURPOSES ONLY

2013. "Downstream approaches to phosphorus management in agricultural landscapes: Regional applicability and use." *Science of the Total Environment* **442**:263–274.

Krogmann, U., B. F. Rogers, L. S. Boyles, W. J. Bamka, and J. R. Heckman. 2003. "Guidelines for land application of non-traditional organic wastes (food processing by-products and municipal yard wastes) on farmlands in New Jersey." *Bulletin e281*. Rutgers Cooperative Extension, New Jersey Agricultural Experiment Station, Rutgers, The State University of New Jersey. http://www.rce.rutgers.edu/pubs/pdfs/e281.pdf (posted June 2003; verified 28 November 2004).

Likens, G. E., and F. H. Bormann. 1995. *Biogeochemistry of a Forested Ecosystem*, 2nd ed. Springer-Verlag, New York.

Magdoff, F., L. Lanyon, and B. Liebhardt. 1997. "Nutrient cycling, transformations, and flows: Implications for a more sustainable agriculture." *Advances in Agronomy* **60**:2–73.

McNaughton, S. J., F. F. Banyikwa, and M. M. McNaughton. 1997. "Promotion of the cycling of diet-enhancing nutrients by African grazers." *Science* **278**:1798–1800.

Mehlich, A. 1984. "Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant." *Communications in Soil Science and Plant Analysis* **15**:1409–1416.

Moebius-Clune, B. N., M. Carlson, H. M. v. Es, J. J. Melkonian, A. T. DeGaetano, and L. Joseph. 2014. "Adapt-n training manual: A tool for precision n management in corn," Extension Series No. E14-1, Edition 1.0. Cornell University, Ithaca, NY. http://adapt-n.cals.cornell.edu/manual/pdfs/adapt-n-manual.pdf.

Olson, R. A., K. D. Frank, P. H. Graboushi, and G. W. Rehm. 1982. "Economic and agronomic impacts of varied philosophies of soil testing." *Agronomy Journal* **74**:492–499.

Owens, L. B., M. J. Shipitalo, and J. V. Bonta. 2008. "Water quality response times to pasture management changes in small and large watersheds." *Journal of Soil and Water Conservation* **63**:292–299.

Perry, D. A. 1994. *Forest Ecosystems*. Johns Hopkins University Press, Baltimore, MD.

Peters, J. 2012. "Manure analysis update: 1998–2010," presentation. Department of Soil Science, University of Wisconsin, Madison, WI. http://www.soils.wisc.edu/extension/area/2010/Manure_summary_Peters.pdf.

Poffenbarger, H.J., S.B. Mirsky, R. R. Weil, M. Kramer, J.T. Spargo, and M.A. Cavigelli. 2015. "Legume proportion, poultry litter, and tillage effects on cover crop decomposition." *Agronomy Journal* 107:2083–2096.

Pote, D. H., and J. J. Meisinger. 2014. "Effect of poultry litter application method on ammonia volatilization from a conservation tillage system." *Journal of Soil and Water Conservation* **69**:17–25.

Pote, D., T. Way, P. Kleinman, P. Moore, J. Meisinger, K. Sistani, L. Saporito, A. Allen, and G. Feyereisen. 2011. "Subsurface application of poultry litter in pasture and no-till soils." *Journal of Environmental Quality* **40**:402–411.

Powers, J. F., and W. P. Dick (eds.). 2000. *Land Application of Agricultural, Industrial, and Municipal By-Products*, Soil Science Society of America Book Series No. 6. Soil Science Society of America, Madison, WI.

Preusch, P. L., P. R. Adler, L. J. Sikora, and T. J. Tworkoski. 2002. "Nitrogen and phosphorus availability in composted and uncomposted poultry litter." *Journal of Environmental Quality* **31**:2051–2057.

Qualls, R. G., B. L. Haines, and W. T. Swank. 2014. "Soluble organic nutrient fluxes," pp. 85–101. In W. T. Swank and J. R. Webster (eds.). *Long-Term Response of a Forest Watershed Ecosystem: Clearcutting in the Southern Appalachians*. Oxford University Press, New York, p. 272.

Reddy, G. B., and K. R. Reddy. 1993. "Fate of nitrogen-15 enriched ammonium nitrate applied to corn." *Soil Science Society of America Journal* **57**:111–115.

Reid, D. K., B. Ball, and T. Q. Zhang. 2012. "Accounting for the risks of phosphorus losses through tile drains in a phosphorus index." *Journal of Environmental Quality* **41**:1720–1729.

Reuter, D. J., and J. B. Robinson. 1986. *Plant Analysis: An Interpretation Manual*. Inkata Press, Melbourne, Australia.

Ribaudo, M., J. Savage, and M. Aillery. 2014. "An economic assessment of policy options to reduce agricultural pollutants in the Chesapeake Bay," ERR - 166. U.S. Department of Agriculture, Economic Research Service, Washington, DC. www.ers.usda.gov/publications/err-economic-research-report/err166.aspx.

Richards, R. P., et al. 1996. "Well water, well vulnerability, and agricultural contamination in the midwestern United States." *Journal of Environmental Quality* **25**:389–402.

Ryals, R., and W. L. Silver. 2013. "Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands." *Ecological Applications* **23**:46–59.

Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. "Concepts and rationale for regional nitrogen rate guidelines for corn," PM 2015. Iowa State University, Ames, IA. https://store.extension.iastate.edu/Product/pm2015-pdf.

Serra, A. P., D. J. Bungenstab, M. E. Marchetti, F. C. N. Guimarães, V. D. A. Conrad, H. S. d. Morais, M. A. G. d. Silva, and R. P. Serra. 2013. "Diagnosis and recommendation integrated system (dris) to assess the nutritional state of plants." In M. D. Matovic (ed.). *Biomass Now-Sustainable Growth and Use*. InTech.

Sharpley, A. N. 1997. "Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter." *Journal of Environmental Quality* **26**:1127–1132.

Smaling, E. M. A., S. M. Nwanda, and B. H. Jensen. 1997. "Soil fertility in Africa is at stake." In R. J. Buresh,

FOR REFERENCE PURPOSES ONLY

P. A. Sanchez, and F. Calhoun (eds.). *Replenishing Soil Fertility in Africa*. ASA/SSSA Publication, Soil Science Society of America, Madison, WI.

Snyder, C. S., T. W. Bruulsema, A. N. Sharpley, and D. B. Beegle. 2005. *Site-Specific Use of the Environmental Phosphorus Index Concept*. Potash & Phosphate Institute, Norcross, GA, p. 4.

Sommer, S. G., M. L. Christensen, T. Schmidt, and L. S. Jensen (eds.). 2013. *Animal Manure Recycling: Treatment and Management*. John Wiley, New York, pp. 1–367.

Sutton, A. L. 1994. "Proper animal manure utilization," in *Nutrient Management*, supplement to *Journal of Soil Water Conservation* 49(2): 65–70.

Swank, W. T., J. M. Vose, and K. J. Elliot. 2001. "Long-term hydrologic and water quality responses following commercial clear cutting of mixed hardwoods on a southern Appalachian catchment." *Forest Ecology and Management* 143:163–178.

Tiessen, K. H. D., J. A. Elliott, J. Yarotski, D. A. Lobb, D. N. Flaten, and N. E. Glozier. 2010. "Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies." *Journal of Environmental Quality* 39:964–980.

USDA Natural Resources Conservation Service. 2007. *The P Index: A Phosphorus Assessment Tool*. www.nrcs.usda.gov/TECHNICAL/ECS/nutrient/pindex.html (confirmed July 2007).

Weil, R. R., and S. K. Mughogho. 2000. "Sulfur nutrition of maize in four regions of Malawi." *Agronomy Journal* 92:649–656.

Wick, J., and J. Creque. 2014. "The Marin Carbon Project: Increasing carbon capture on California's rangelands." Marin Carbon Project Washington State University YouTube. https://www.youtube.com/watch?v=bGWry8jWlmw.

Yang, H. S. 2006. "Resource management, soil fertility and sustainable crop production: Experiences of China." *Agriculture, Ecosystems and Environment* 116: 27–33.

Zhou, X., M. J. Helmers, H. Asbjornsen, R. Kolka, M. D. Tomer, and R. M. Cruse. 2014. "Nutrient removal by prairie filter strips in agricultural landscapes." *Journal of Soil and Water Conservation* 69:54–64

Zublena, J. P., J. C. Barker, and T. A. Carter. 1993. "Poultry manure as a fertilizer source." *Soil Facts*. North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, NC.

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17
Soil Erosion and Its Control

The wind crosses the brown land, unheard . . .
—*T. S. Eliot*, The Waste Land

Degraded land and livelihoods, Kisongo, Tanzania. (Ray R. Weil)

The first 16 chapters of this book teach us about Earth's incredibly intricate soil ecosystems, how they function to support life, and how we can best preserve and enhance their health and productivity. Now we must consider how these complex biological-physical–chemical systems are threatened with degradation and destruction by the very people they support. In a world with ever more people, but never more land, no challenge can be more central to human survival than proper care of land and soil. Soil erosion is the most destructive outcome of poor soil and land management. Throughout history people have brought the scourge of soil erosion upon themselves, suffering impoverishment and hunger in its wake. Past civilizations have disintegrated as their soils, once deep and productive, were washed or blown away, leaving only thin, rocky relics of the past. Lakes, rivers, harbors, and estuaries have been silted-in with the lost sediment and entire coastlines transformed.

From expanding cities to shrinking forests, humans acting out of ignorance or greed or just carelessness continue to expose bare soils with devastating results. As the ratio of people to land steadily rises, poor people see little choice but to clear and burn steep, forested slopes or plow up natural grasslands to plant their crops. Population pressures have also led to overgrazing of rangelands and overexploitation of timber resources. All these activities lead to a downward spiral of ecological deterioration, land degradation, and deepening poverty. The impoverished crops and rangelands leave little if any plant litter to protect the soil, leading to further erosion, driving ever more desperate people to clear and cultivate—and degrade—still more land. Add to this the intense, concentrated erosion on sites disturbed by urbanization, construction, or mining activity, as well as globalization pressures to expand cropping and logging to marginal lands, and it is clear that the current threat of soil erosion is more ominous than at any time in history.

The degraded productivity and loss of ecosystem services from farm, forest, range, and urban lands tells only part of the sad erosion story. Soil particles washed or blown from the eroding areas are subsequently deposited elsewhere—in nearby low-lying sites within the landscape or far away—even on other continents. Far downstream or downwind, the sediment and dust cause major pollution of water and air and bring enormous economic and social costs to society.

Combating soil erosion is everybody's responsibility and to everyone's advantage. Fortunately, much has been learned about the mechanisms of erosion and techniques have been developed that can effectively and economically control soil loss in most situations. This chapter will equip you with some of the concepts and tools you will need to do your part in solving this pressing world problem.

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17.1 SIGNIFICANCE OF SOIL EROSION AND LAND DEGRADATION[1]

Land Degradation

Land degradation may be defined as a reduction in the capacity of land to provide ecosystem goods and perform functions and services that support society and nature (The Millennium Ecosystem Assessment, http://www.millenniumassessment.org/). Determining the extent of land degradation remains a rather inexact science, with most recent efforts dependent on satellite-collected spectral imagery (see Section 19.4) in which measures of "greenness" correlate with the amount and vigor of *vegetative* cover. Sensing changes in *soil* conditions by remote sensing is much more difficult, except in the areas where unvegetated bare soils are exposed because of aridity or agricultural tillage. During the past century, human land use and associated activities may have degraded almost half (some 5 billion ha) of the Earth's vegetated land to some degree. Much of this degradation (on about 2.5 billion ha) is linked to **desertification**, the spreading of desert-like conditions that disrupt semiarid and arid ecosystems (including agroecosystems). A major cause of desertification is poorly managed grazing by cattle, sheep, and goats, a process that likely accounts for about a third of all land degradation, mainly in such dry regions as northern Africa, western China, and the American Southwest. Likewise, the indiscriminate felling of rain forest trees has already degraded about 0.5 billion ha in the humid tropics. Additionally, inappropriate agricultural practices continue to degrade land in all climatic regions.

Soil-Vegetation Interdependency

Degraded lands may suffer from destruction of native vegetation communities, reduced agricultural yields, lowered animal production, and simplification of once-diverse natural ecosystems with or without equally severe degradation of the soil resource. On about 2 billion of the 5 billion ha of degraded lands in the world, soil degradation is a major part of the problem (Figure 17.1). Degradation of soils occurs in many ways (Table 17.1). In some cases the soil degradation occurs mainly as deterioration of physical properties by compaction or surface crusting (see Sections 4.7 and 4.6), or as deterioration of chemical properties by acidification (see Section 9.6) or salt accumulation (see Section 10.3). Although the table separates physical, chemical, and biological degradation, in reality soils are complex systems in which these processes interact and influence one another. However, most (~85%) soil degradation stems from erosion—the movement of soil material by wind, water, or tillage implements. The two main components of land degradation—damage to plant communities and deterioration of soil—commonly interact to cause a downward spiral of accelerating ecosystem damage and human poverty (Figure 17.2). Due to overgrazing, deforestation, or inappropriate methods of crop production, vegetation becomes less dense and vigorous, and thus provides the soil with less and less protection from erosion. Simultaneously, erosion and nutrient depletion make the soil less and less capable of supporting a protective canopy of vegetation. Soil degradation limits the water available to vegetation through its effects on runoff and infiltration of rainwater (see Section 6.2). With as much as 50–60% of the rainfall lost as runoff, scarcity of soil water on eroded soils can become a serious impediment to plant growth. Improvements in both soil and vegetation management must go hand-in-hand if the productive potential of the land is to be protected. Moreover, a more challenging, but attainable goal, may be to restore and enhance productivity by moving up rather than down the spiral.

Geological Versus Accelerated Erosion

Geological Erosion. Erosion is a process that transforms soil into **sediment**. Soil erosion that takes place naturally, without the influence of human activities, is termed **geological erosion**. It is a natural leveling process. It inexorably wears down hills and mountains, and

[1]For a readable account of historical degradation of land and water resources, see Hillel (1991). The global areas affected by soil erosion and other forms of global land degradation have been variously estimated using remote sensing and ground-based methods (de Jong et al., 2011; Hosonuma et al., 2012; Lambin and Meyfroidt, 2011; Montgomery, 2007; Oldeman, 1994).

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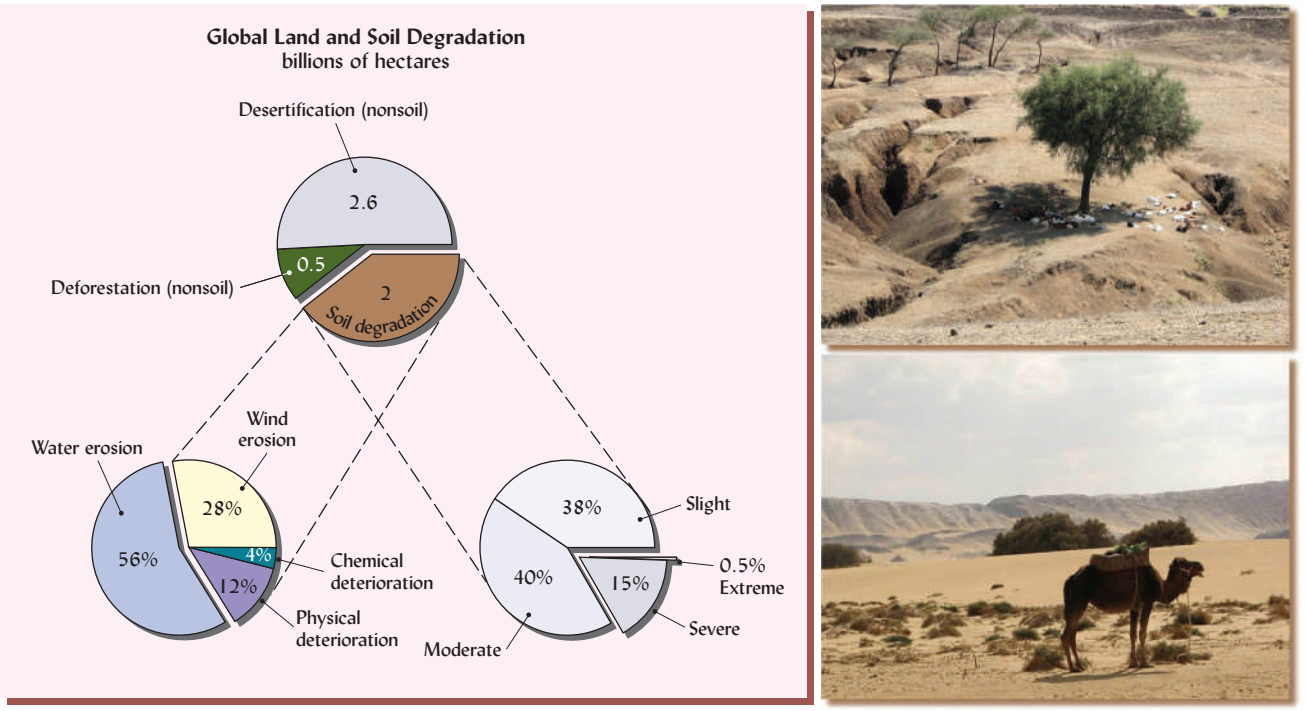

Figure 17.1 *Soil degradation is a part of global land degradation caused by overgrazing, deforestation, inappropriate agricultural practices, fuel wood overexploitation, urbanization, and other human activities. According to FAO estimates, about 60% of degraded land has suffered vegetative degradation, but the soil is not yet seriously impaired. Of the 2 billion ha of land that does have degraded soils, most are only slightly or moderately degraded and could be restored with local financial and technical investments. Severely degraded soils are currently useless for agriculture and those in lesser developed countries would require major international assistance for restoration. About 10 million ha (0.5% of degraded soils) are extremely degraded and incapable of restoration. About 85% of soil degradation is caused by erosion by wind (*lower right*) and water (*upper right*), much of it aggravated by tillage or by poor grazing management as illustrated in the photos.* [FAO data selected from Oldeman (1994) and Daily (1997); Photos courtesy Ray R. Weil]

through subsequent deposition of the eroded sediments, it fills in valleys, lakes, and bays. Many of the landforms we see around us—canyons, buttes, rounded mountain remnants, river valleys, deltas, plains, and pediments—are the result of geological erosion and deposition. The vast deposits that now appear as sedimentary rocks originated in this way.

In most settings, geological erosion wears down the land slowly enough that new soil forms from the underlying rock or regolith faster than the old soil is lost from the surface. The very existence of soil profiles bears witness to the net accumulation of soil and the effectiveness of undisturbed natural vegetation in protecting the land surface from erosion.

The rate of geological soil erosion varies greatly with both rainfall and type of material comprising the regolith. Geological erosion by water tends to be greatest in semiarid regions where rainfall is enough to be damaging, but not enough to support dense, protective vegetation (Figure 17.3). Areas blanketed by deep deposits of silts may have exceptionally high erosion rates under such conditions. The gullied, barren landscape of the North American badlands (Figure 17.4, *left*) is an extreme example of geological erosion occurring where unstable clay and silt deposits are subjected to infrequent but intense rainstorms, yet the soil is usually too dry (partly because of high runoff losses) to support much protective vegetation.

Sediment Loads. Rainfall, geology, and other factors (including human activities) influence the sediment loads carried by the world's great rivers (Table 17.2). Note the relatively low erosion rates per hectare of land for the rivers that drain landscapes mainly at the extreme humid forested (Amazon and Mekong) or arid (Nile) ends of the scale in Figure 17.3. Although rivers like the Ganges and Yangtze, which drain largely semiarid regions, were muddy before

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Table 17.1
MAJOR TYPES OF SOIL DEGRADATION AND THE CONDITIONS UNDER WHICH THEY ARE MOST COMMONLY FOUND

Although the table separates physical, chemical, and biological degradation, in reality soils are complex systems in which these processes interact and influence one another. The first three processes listed, erosion by water, wind, and tillage, together dominate soil degradation on the vast majority of land area degraded.

Category	Specific degradation processes	Conditions and locations where most prominent
Physical	Soil erosion by water	Associated with tillage agriculture, deforestation, and improper grazing on sloping lands in humid to semiarid regions.
	Soil erosion by wind	Semiarid to arid regions. Disturbance of soil, vegetation, or bio-crust by agricultural tillage and improper grazing or trafficking.
	Soil erosion by tillage	Hilly landscapes under continuous cultivation, especially with tillage up and downslope. May aggrade concave areas while degrading hilltops.
	Surface sealing	Hydrologic sealing of the soil surface results from pavement and compaction in urban areas, and from excessive tillage in croplands, especially those with low organic matter sandy or silty soils.
	Soil compaction	Clayey soils in humid regions trafficked by heavy machinery suffer the most pervasive compaction problems. European farmland accounts for almost half of the global degradation by compaction.
	Reduced capacity to store water	Areas where soil depth is reduced by erosion, porespace is reduced by compaction, or water holding capacity is reduced by loss of soil organic matter or mulch layer.
Biological	Loss of soil biological diversity	Soil biodiversity usually reflects the diversity of plants and animals supported, thus monocropping, deforestation, and poorly managed grazing are most often associated with low soil biodiversity.
	Depletion of soil organic matter	Degradation of vegetation, excessive tillage, lack of sufficient organic amendments and plant residues; excessive biomass removal by harvest, grazing, or fire; erosion of high organic surface soil; burial of downslope surface soil under eroded sediments.
	Loss of plant, animal, and microbial biomass	Reduced plant growth and subsequent addition of litter, roots, and exudates limits carbon fuel for food web; exposure to extremes of dryness and temperature by removal of plant litter; destruction of macropores, aggregates, and other habitat by tillage, compaction, and erosion.
Chemical	Nutrient depletion	Low input agriculture, overgrazing, excessive forest harvest, loss by erosion
	Salinization	Arid to semiarid regions, shallow water table, excessive irrigation, removal of native vegetation
	Dispersion/alkalization	Excessive monovalent ions, poor quality irrigation water, loss of perennial vegetation, exposure and incorporation into the surface horizon of calcareous subsoil material as a result of erosion by tillage and wind.
	Acidification	Excessive N fertilization, cation leaching, sulfur and nitrogen oxidation
	Toxic contamination	Urbanization, mining, industrial waste spillage or disposal, smelting fumes, pesticide application, use of metal-contaminated amendments

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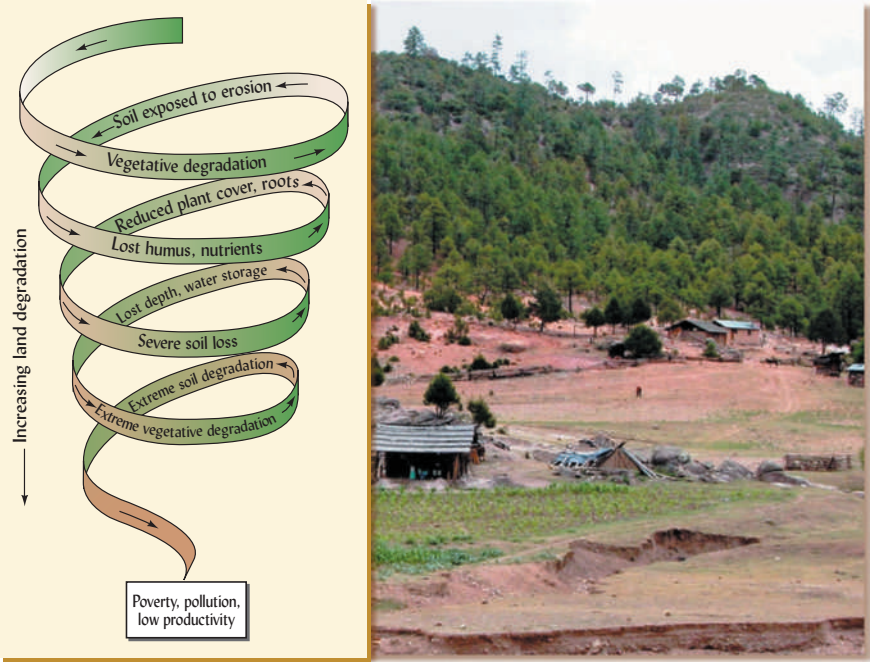

Figure 17.2 *The downward spiral of land degradation resulting from the feedback loop between soil and vegetation. As the natural vegetation is disturbed, soil becomes exposed to raindrops and wind leading to erosion and loss of soil, including organic matter and nutrients. The now impoverished soil can support only stunted crops or other vegetation, which leaves the soil with even less protective cover and root mass than before. As more soil loss occurs, the soil becomes extremely degraded and even less protected. Incapable of providing nutrients and water needed to support healthy natural vegetation or crops, the soil continues to erode, polluting rivers with sediment and impoverishing the people who attempt to grow their food and lumber on the land.* (Photo of indigenous village in Mexico and diagram courtesy Ray R. Weil)

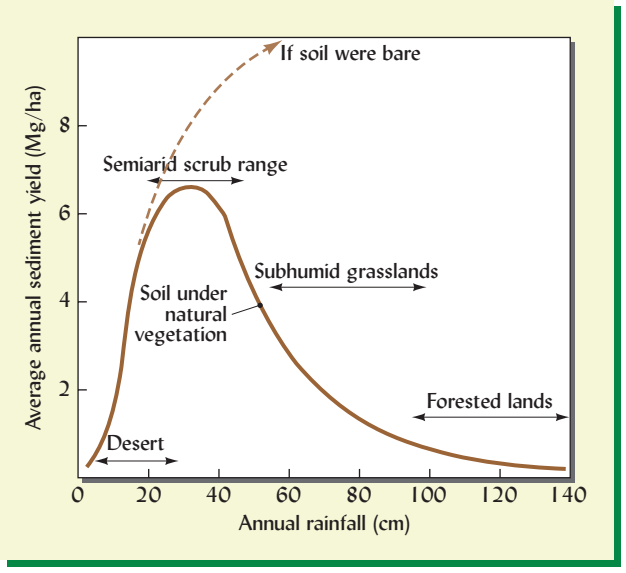

Figure 17.3 *Generalized relationship between annual rainfall and soil loss from geologic erosion by water. The actual amount of sediment lost annually per hectare will depend on other climatic variables, topography, and the type of soils in the watershed. Note that sediment yields are greatest in semiarid regions. Here a number of severe runoff–generating storms occur in most years, but the total rainfall is too little to support much protective plant cover. By comparison, the very dry deserts have too little rain to cause much erosion, and the well-watered regions support dense forests that effectively protect the soil. Where the natural vegetation is destroyed by plowing, erosion from the bare soils is much higher with increasing rainfall, as indicated by the dashed curve.* (Diagram courtesy Ray R. Weil)

humans disturbed their watersheds, current sediment loads are far greater than before. To gain some perspective on the enormous amount of soil transported to the sea by such rivers, consider the Mississippi's sediment load (only a fifth as great as that of the Yangtze or the Ganges). If the 300 million Mg of sediment were carried to the Gulf of Mexico by dump trucks, it would take a continuous, year-round caravan of more than 80,000 large trucks, stretching all the way from Wisconsin to New Orleans (1600 km) in the United States and back, with a 20-Mg load being dumped into the Gulf about every 2 seconds.

Human-Accelerated Erosion.[2] We stand in awe at the edge of the Grand Canyon in the United States, which was formed over millennia by geologic erosion—yet few realize that

[2]For a geo-historical study of 100-fold human-accelerated erosion in the nineteenth century following deforestation for farming in the southeastern United States, see Reusser et al. (2015).

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Figure 17.4 *The effects of geologic erosion and sedimentation can be dramatic. In the scene from South Dakota's semiarid badlands in the United States (left) there is little vegetation to protect the hills from ravages of sudden summer thunderstorms. Deep layers of clayey sediment had been deposited on this site during ancient cycles of erosion and sedimentation. A scene in central Tanzania (right) highlights the cutting power of turbulent water and the important role of raindrops in detaching soil particles. Note the tall, thin pedestals of soil that remain where a layer of rocklike ironstone protects the underlying soft material from the impact of raindrops (compare to the much smaller pedestals in Figure 17.10a).* (Photos courtesy of Ray R. Weil)

Table 17.2
ANNUAL SEDIMENT LOADS FOR NINE OF THE WORLD'S MAJOR RIVERS

River	Countries	Annual sediment load, million Mg	Erosion, Mg/ha drained
Yangtze	China	1600	479
Ganges	India, Nepal	1455	270
Amazon	Brazil, Peru, etc.	363	13
Mississippi	United States	300	93
Irrawaddy	Burma	299	139
Kosi	India, Nepal	172	555
Mekong	Vietnam, Thailand, etc.	170	43
Red	China, Vietnam	130	217
Nile	Sudan, Egypt, etc.	111	8

Data from different sources compiled by El-Swaify and Dangler (1982).

humankind has become the preeminent force on the landscape, now moving nearly twice as much soil per year as global geologic process, and two-thirds of that *unintentionally* through erosion, mainly associated with agricultural activities (Figure 17.5).

Accelerated erosion occurs when people disturb the soil or the natural vegetation by overgrazing livestock, cutting forests for agricultural use, plowing hillsides (Figure 17.6, *left*), or tearing up land for construction of roads and buildings. Accelerated erosion is often 10–1000 times as destructive as geological erosion, especially on sloping lands in regions of high rainfall. Rates of erosion by wind and water on agricultural land in Africa, Asia, and South America are thought to average about 30–40 Mg/ha annually. In North America, the *average* erosion rates on cropland by water and wind are 7 Mg and 5 Mg/ha, respectively. Some cultivated soils are eroding at ten times these average rates. In comparison, erosion

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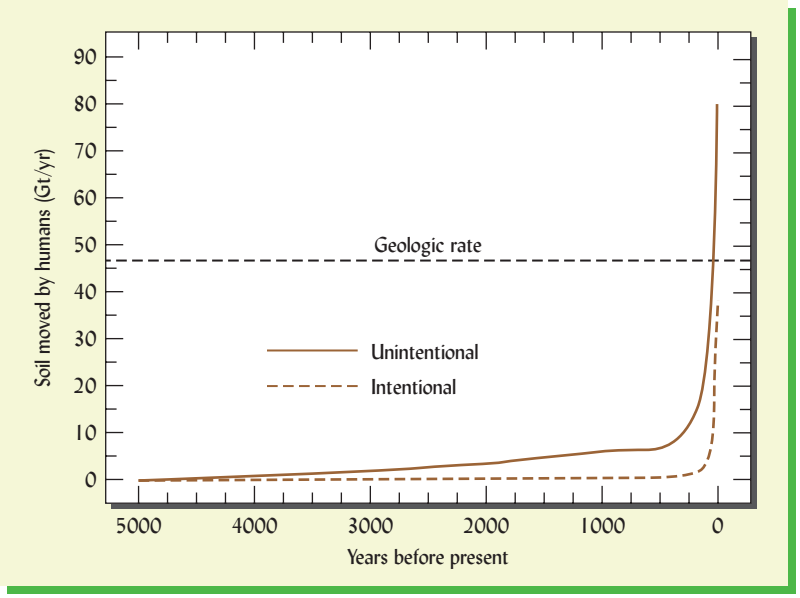

Figure 17.5 *The amount of soil moved by human beings. Intentional soil movement refers mainly to construction and excavation activities. Unintentional soil movement refers mainly to soil loss due to agricultural activities such as land clearing, tillage, overgrazing, and long periods without vegetative cover. Humans now move more soil material than all natural processes combined. This may not mean that sediment loads of major rivers have increased this dramatically, as all movement of soil within a landscape does not necessarily lead to sediment in rivers.* [For comparisons of agricultural to geologic soil movement, see Wilkinson and McElroy (2007). Graph redrawn from Hooke (2000)]

Figure 17.6 *Erosion and deposition occur simultaneously across a landscape.* (Left) *The soil on this hilltop was worn down by water and tillage erosion during nearly 300 years of cultivation. The surface soil exposed on the hilltop consists mainly of light-colored C horizon material. At sites lower down the slope the surface horizon shows mainly darker-colored A and B horizon material, some of which has been deposited after eroding from locations upslope.* (Right) *Erosion on the sloping wheat field in the background has deposited a thick layer of sediment in the foreground, burying the plants at the foot of the hill.* (Photos courtesy of Ray R. Weil (*left*) and USDA Natural Resources Conservation Service (*right*))

on undisturbed humid-region grasslands and forests generally occurs at rates considerably below 0.1 Mg/ha.

About 4 billion Mg of soil is moved annually by soil erosion in the United States, some two-thirds by water, one-third by wind. More than half of the movement by water and about 60% of the movement by wind take place on croplands that produce essential food supplies. Some of this cropland also suffers from soil relocation during tillage operations. Much of the remaining erosion comes from semiarid rangelands, from logging roads and timber harvest on forest lands, and from soils disturbed for highway and building construction. Although progress has been made in reducing erosion (see Section 17.14), current losses are simply too great for long-term sustainability and must be further reduced.

Under the influence of accelerated erosion, soil is commonly washed, blown, or scraped away faster than new soil can form by weathering or deposition. As a result, the soil depth

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suitable for plant roots is often reduced. In severe cases, sloping terrain may become scarred by deep gullies, and once-forested hillsides may be stripped down to bare rock. Accelerated erosion often makes the soils in a landscape more heterogeneous. An example can be seen in the striking differences in surface soil color that develop as hilltop soils are truncated, exposing material from the B or C horizon at the land surface, while soils lower in the landscape are buried under organic-matter-enriched sediment (Figure 17.6, *right*). Much of such soil movement occurs during tillage.

17.2 ON-SITE AND OFF-SITE IMPACTS OF ACCELERATED SOIL EROSION

Erosion damages the site on which it occurs and also has undesirable effects off-site in the larger environment. The off-site costs relate to the effects of excess water, sediment, dust, and associated chemicals on downhill, downwind, and downstream environments. While the costs associated with either or both of these types of damages may not be immediately apparent, they are real and grow with time. Landowners and society as a whole eventually foot the bill.

Types of On-Site Damages

The most obviously damaging aspect of erosion is the loss of soil itself. In reality, the damage done to the soil is greater than the amount of soil lost would suggest, because the soil material eroded away was almost always more valuable than that left behind. Not only are surface horizons eroded while less fertile subsurface horizons remain untouched, but the quality of the remaining topsoil is also impaired. Erosion by wind and water selectively removes organic matter and fine mineral particles, while leaving behind mainly relatively less active, coarser fractions. Experiments have shown organic matter and nitrogen in the eroded material to be on average five times as high as in the original topsoil, giving an **enrichment ratio** of 5 for these soil components. Comparable enrichment ratios for phosphorus and potassium are commonly between 2 and 3. The quantity of essential nutrients lost from the soil by erosion is quite high, although only a portion of these nutrients are lost in forms that would be available to plants in the short term. The soil left behind usually has lower water-holding and cation exchange capacities, less biological activity, and a reduced capacity to supply nutrients for plant growth.

In addition to the just-mentioned reduction in soil-quality factors, soil movement during erosion can spread plant disease organisms from the soil to plant foliage and from higher to lower-lying areas in a field. The deterioration of soil structure often leaves a dense crust on the soil surface, which, in turn, greatly reduces water infiltration and increases water runoff. Newly planted seeds and seedlings may be washed downhill, trees may be uprooted, and small plants may be buried in sediment. Finally, gullies that carve up badly eroded land may make the use of field equipment impossible and may undercut pavements and building foundations, causing unsafe conditions and expensive repairs.

Types of Off-Site Damages

Erosion moves sediment and nutrients off the land, creating the two most widespread water pollution problems in our rivers and lakes. The nutrients impact water quality largely through the process of eutrophication caused by excessive nitrogen and phosphorus, as was discussed in Sections 13.8 and 14.2. In addition to nutrients, sediment and runoff water may also carry toxic metals and organic compounds, such as pesticides. The sediment itself is a major water pollutant, causing a wide range of environmental damages.

Damages from Sediment. Sediment deposited on the land may smother crops and other low-growing vegetation (Figure 17.6, *right*). It fills in roadside drainage ditches and creates hazardous driving conditions where mud covers the roadway.

Sediment that washes into streams makes the water cloudy or turbid (Figure 17.7). High **turbidity** prevents sunlight from penetrating the water and thus reduces photosynthesis and survival of the *submerged aquatic vegetation* (SAV). The demise of the SAV, in turn, degrades the fish habitat and upsets the aquatic food chain. The muddy water also fouls the gills of

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Figure 17.7 *Off-site damages caused by soil erosion include the effects of sediment on aquatic systems.* (Left) *A sediment-laden tributary stream empties into the relatively clear waters of a larger river. The turbid water will foul fish gills, inhibit submerged aquatic vegetation, and clog water-purification systems. Part of the sediment will settle out on the river bottom, covering fish-spawning sites and raising the river bed enough to aggravate the severity of future flooding episodes.* (Middle) *A NASA satellite image shows the heavy sediment loads (yellow) entering the Chesapeake Bay on the US Atlantic coast from major tributary rivers such as the Potomac in the west and the Susquehanna in the north.* (Right) *Expensive dredging and excavation (by the dragline in the foreground) is being undertaken to restore the beauty, recreational, and wildlife value, and flood-control function of this pond in a neighborhood park after accumulated sediment had transformed it into a mere mudflat. The watershed upstream from the pond had undergone a period of rapid suburban development, during which adequate sediment-control practices were not used on the construction sites.* (Photos courtesy of USDA Natural Resources Conservation Service (*left*), NASA (*middle*), and Ray R. Weil (*right*))

some fish. Sediment deposited on the stream bottom can have a disastrous effect on many freshwater fish by burying the pebbles and rocks among which they normally spawn. The buildup of bottom sediments can actually raise the level of the river, so that flooding becomes more frequent and more severe. For example, to counter the rising river bottom, flood-control levees along the Mississippi River must be constantly enlarged.

A number of major problems occur when the sediment-laden rivers reach a lake, reservoir, or estuary. Here, the water slows down and drops its load of sediment. Eventually reservoirs—even those formed by giant dams—become mere mudflats, completely filled in with sediment (see Figure 17.7, *right*). Prior to that, the capacity of the reservoir to store water for irrigation or municipal water systems is progressively reduced, as is the capacity for floodwater retention or hydroelectric generation. Similarly, harbors and shipping channels fill in and become impassible. The loss of function and the costs of dredging, excavation, filtering, and construction activities necessary to remedy these situations run into billions of dollars every year.

Windblown Sand and Dust. Wind erosion also has its off-site effects. Blowing sands may bury roads and fill in drainage ditches, necessitating expensive maintenance. The sandblasting effect of wind-borne soil particles may damage the fruits and foliage of crops in neighboring fields, as well as the paint on vehicles and buildings many kilometers downwind from the eroding site. Finer wind-blown dust with clay-size particles causes the most expensive and far-reaching damages. Much of this dust—especially particulate matter (PM) with diameters between 2.5 and 10 microns (**PM_{10}**)—arises from wind erosion on cropland, rangelands, and construction sites (as well as from traffic on unpaved roads). Even more damaging are particles smaller than 2.5 microns (**$PM_{2.5}$**), which arise mainly from vehicle exhaust and smoke from fires and industrial plants. The off-site damages from these dust particles include the aesthetics-related costs of added housecleaning, more frequent car washes, and lost tourism revenues when majestic views at recreational parks are obscured. Even more serious are the major health hazards presented when people inhale these very fine wind-blown particles.

Health Hazards from PM_{10} and $PM_{2.5}$.[3] While silt-sized particles are generally filtered by nose hairs or trapped in the mucous of the windpipe and bronchial tubes, smaller clay-sized particles often pass through these defenses and lodge in the alveoli (air sacs) of the

[3]For details about health effects of PM_{10} and $PM_{2.5}$, see WHO (2013).

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lungs. The particles themselves cause inflammation of the lungs, and they may also often carry toxic substances that cause further lung damage. For example, airborne clay particles adsorb water vapor and may become coated with sulfuric or nitric acids found in the atmosphere (see Section 9.6). Human pathogens may also adhere to dust particles and travel with them to spread disease.

Epidemiological studies suggest that the number of deaths resulting from people inhaling this fine *fugitive dust* is in the thousands every year, and may even exceed the number of deaths from traffic accidents. The U.S. Environmental Protection Agency therefore has set standards that call for the 24-hour average concentrations in the air not to exceed 150 and 35 $\mu g/m^3$ of PM_{10} and $PM_{2.5}$, respectively. However, windblown dust is a global problem. For example, wind erosion in the Sahara desert in Africa and Gobi desert in China has been implicated in respiratory diseases in North America.

Estimated Costs of Erosion.[4] Although no precise data exist, national or regional average wind water and tillage erosion rates can be used to estimate the total costs of erosion. Included in such calculations are the on-site costs of replacing nutrients and water lost through accelerated erosion, as well as crop yield reductions due to reduced soil depth on the shoulder slopes and burial of topsoil under sediment on lower slopes. Depending mainly on assumptions about the value of nutrients lost in sediment and runoff (should only those in readily useable form be valued?), the total annual on-site costs in the United States have been estimated at between $10 and $50 billion.

The off-site costs of erosion are likely even greater, especially because of the health effects of windblown particles and the reduced recreational (fishing, swimming, and aesthetic) value of muddy waters. The total of these annual off-site costs has been estimated at between $12 and $40 billion. The grand total annual cost of erosion in the United States is therefore likely between $22 and $90 billion. Worldwide soil erosion on agricultural land annually imposes more than $500 billion in combined on-site and off-site impacts. Such high costs are a sobering reminder of the burden that society bears as a result of poor land management and would seem to justify substantial increases in the sums allocated to the battle against erosion.

Maintenance of Soil Productivity.[5] Although extreme soil erosion can eventually reduce soil productivity to almost zero (as when only exposed rock remains), in most cases the effect is too subtle to notice between one year and the next. Where farmers can afford to do so, they compensate for the loss of nutrients by increasing the use of fertilizer. The losses of organic matter, rooting depth, and water-holding capacity are much more difficult to overcome, though irrigation may partially do so.

Over the long term, accelerated soil erosion that exceeds the rate of soil formation leads to declining productivity on most soils. In North America, crop yields on severely eroded soils are commonly 20–40% lower than on similar soils with only slight erosion. Initially, the main effect of erosion losses over time is that each year plowing mixes a greater proportion of low organic matter subsoil material into the "topsoil" layer. This action will deleteriously alter the composition of the plowed topsoil as erosion advances. Once the "topsoil" consists mainly of subsoil material from the former B horizon, further erosion may not greatly further reduce the quality of the "topsoil" as a growth medium. However, erosion would continue to reduce the rooting volume available, especially if the profile contains layers that are impermeable, acidic, alkaline, calcareous, or otherwise inhospitable to root growth.

Ultimately, the rate of decline of soil productivity, or the cost of maintaining constant food production levels, is determined by such soil properties as *depth to a root-restricting layer* and *permeability or chemical favorability of the subsoil.* As shown in Figure 17.8, a deep, permeable, well-drained, and well-managed soil may not decline much in productivity even though it suffers some erosion. In contrast, erosion on a shallow, low-permeability soil may bring about a rapid productivity decline.

[4]A detailed analysis giving estimates in 1995 dollars can be found in Pimentel et al. (1995).

[5]Research models can simulate how soil productivity may decline as erosion advances over time and the plow layer composition comes to include less organic matter and more and more subsoil material (Gao et al., 2015).

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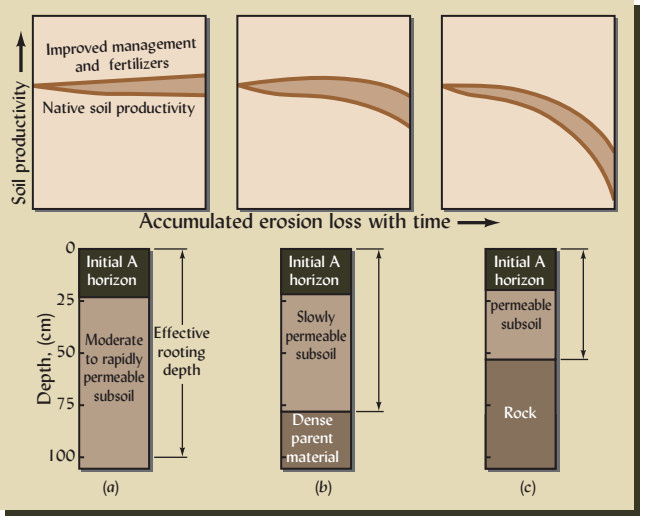

Figure 17.8 *Effect of erosion over time on the productivity of three soils initially differing in depth and permeability. Productivity on soil (a) actually increases with time because of improving management practices and fertilizer additions, even though the native soil productivity declines slowly as a result of erosion. Because soil (c) is shallow and has restricted permeability, its productivity declines rapidly as a result of erosion, a decline that improved management and fertilizers cannot prevent. Soil (b), which is intermediate in both depth and permeability, suffers only a slight decline in productivity due to erosion over the period considered. Soil characteristics clearly influence the effect of erosion on soil productivity.* (Diagram courtesy of N. C. Brady and Ray R. Weil)

Soil-Loss Tolerance (*T* values)[6]

The loss of *any* amount of soil by erosion is detrimental, but scientists of the USDA Natural Resources Conservation Service, working in cooperation with field personnel throughout the country, have developed tentative soil-loss tolerance limits for most cultivated soils in the United States. A tolerable soil loss (***T* value**) is considered to be the maximum amount of soil that can be lost annually, on average, by the combination of water and wind erosion on a particular soil without degrading that soil's long-term productivity. To avoid soil losses to exceed *T* in the long term, land management should be designed to reduce soil loss to well below *T* in most years to make up for the much greater losses that inevitably occur in years with unusually erosive storms. Currently, *T* values are based on the best judgment of informed soil scientists, rather than on rigorous research data and "long term" is measured in decades, rather than centuries.

Common Range of *T* Values. The *T* values for soils in the United States commonly range from 5 to 11 Mg/ha, with the majority of agricultural soils assigned the highest *T* value, 11 Mg/ha. This represents a maximum allowable loss of about 0.9 mm of soil depth in an average year, a rate at which it would take about 200 years to lose the equivalent of an entire Ap horizon. Under good agricultural management in a deep, permeable soil profile, this may be sufficient time to allow replacement of the lost material as new Ap horizon material forms from underlying subsoil material. Development of horizons in undisturbed soils under natural vegetation is most likely much slower than this, so the *T* value assigned to a particular type of soil probably would not provide sufficient protection for many rangeland or forest sites. When *T* values are used in determining compliance with various regulatory programs, there is considerable resistance to lowering *T* values even if concerns about long-term soil productivity and about the off-site effects of sediment from eroded fields suggest that they may be too high.

17.3 MECHANICS OF WATER EROSION

Soil erosion by water is fundamentally a three-step process (Figure 17.9):

1. *Detachment* of soil particles from the soil mass.
2. *Transportation* of the detached particles downhill by floating, rolling, dragging, and splashing.
3. *Deposition* of the transported particles at some place lower in elevation.

On comparatively smooth soil surfaces, the beating action of raindrops causes most of the detachment. Where water is concentrated into channels, the cutting action of turbulent,

[6]For a discussion of how *T* values were derived, see Schertz (1983).

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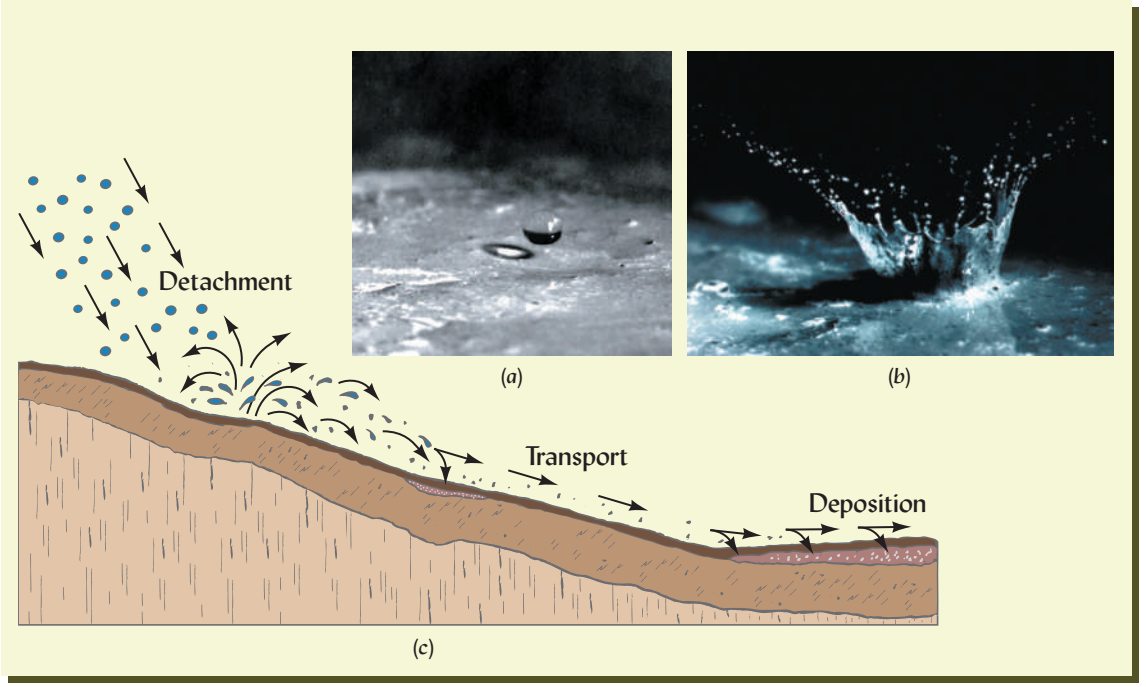

Figure 17.9 *The three-step process of soil erosion by water begins with the impact of raindrops on wet soil. (a) A raindrop speeding toward the ground. (US Navy) (b) The splash that results when the drop strikes a wet, bare soil. Raindrop impact destroys soil aggregates, encouraging sheet and interrill erosion. Also, considerable soil may be moved by the splashing process itself. The raindrop affects the detachment of soil particles, which are then transported and eventually deposited in locations downhill (c).* (Diagram courtesy of Ray R. Weil; (b) US Navy)

flowing water detaches soil particles. In some situations, freezing–thawing action also contributes to soil detachment.

Influence of Raindrops

A raindrop accelerates as it falls until it reaches *terminal velocity*—the speed at which the friction between the drop and the air balances the force of gravity. Larger raindrops fall faster, reaching a terminal velocity of about 30 km/h, or about as fast as an Olympic athlete can run. As the speeding raindrops impact the soil with explosive force, they transfer their high kinetic energy to the soil particles (see Figure 17.9).

Raindrop impact exerts three important detrimental effects: (1) it detaches soil; (2) it destroys granulation; and (3) its splash, under certain conditions, causes an appreciable transportation of soil. So great is the force exerted by raindrops that they not only loosen and detach soil granules, but may even beat the granules to pieces. As the dispersed material dries it may develop into a hard crust, which will prevent the emergence of seedlings and will encourage runoff from subsequent precipitation (see Section 4.6).

History may someday record that one of the truly significant scientific advances of the twentieth century was the realization that most erosion is initiated by the impact of raindrops, rather than the flow of running water. For centuries prior to this realization, soil conservation efforts aimed at controlling the more visible flow of water across the land, rather than protecting the soil surface from the impact of raindrops.

Transportation of Soil

Raindrop Splash Effects. When raindrops strike a wet soil surface, they detach soil particles and send them flying in all directions (see Figure 17.9). On a soil subject to easy detachment, a very heavy rain may splash as much as 225 Mg/ha of soil, some of the particles splashing as much as 0.7 m vertically and 2 m horizontally. If the land is sloping or if the wind is blowing, this splashing may be greater in one direction, leading to considerable net horizontal movement of soil.

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Role of Running Water. Runoff water plays the major role in the transportation step of soil erosion. If the rate of rainfall exceeds the soil's infiltration capacity, water will pond on the surface and begin running downslope. The soil particles sent flying by raindrop impact will then land in flowing water, which will carry them down the slope. So long as the water is flowing smoothly in a thin layer (sheet flow), it has little power to detach soil. However, in most cases the water is soon channeled by irregularities in the soil surface which cause it to increase in both velocity and turbulence. The channelized flow then not only carries along soil splashed by raindrops, but also begins to detach particles as it cuts into the soil mass. This is an accelerating process, for as a channel is cut deeper, it fills with greater and greater volumes of flowing water. So familiar is the power of runoff water to cut and carry that the public generally ascribes to it all the damage done by heavy rainfall.

Types of Water Erosion

Three types of water erosion are generally recognized: (1) *sheet*, (2) *rill*, and (3) *gully* (Figure 17.10). In **sheet erosion**, splashed soil is removed more or less uniformly, except that tiny columns of soil often remain where pebbles intercept the raindrops (see Figure 17.10*a*). However, as the sheet flow is concentrated into tiny channels (termed **rills**),

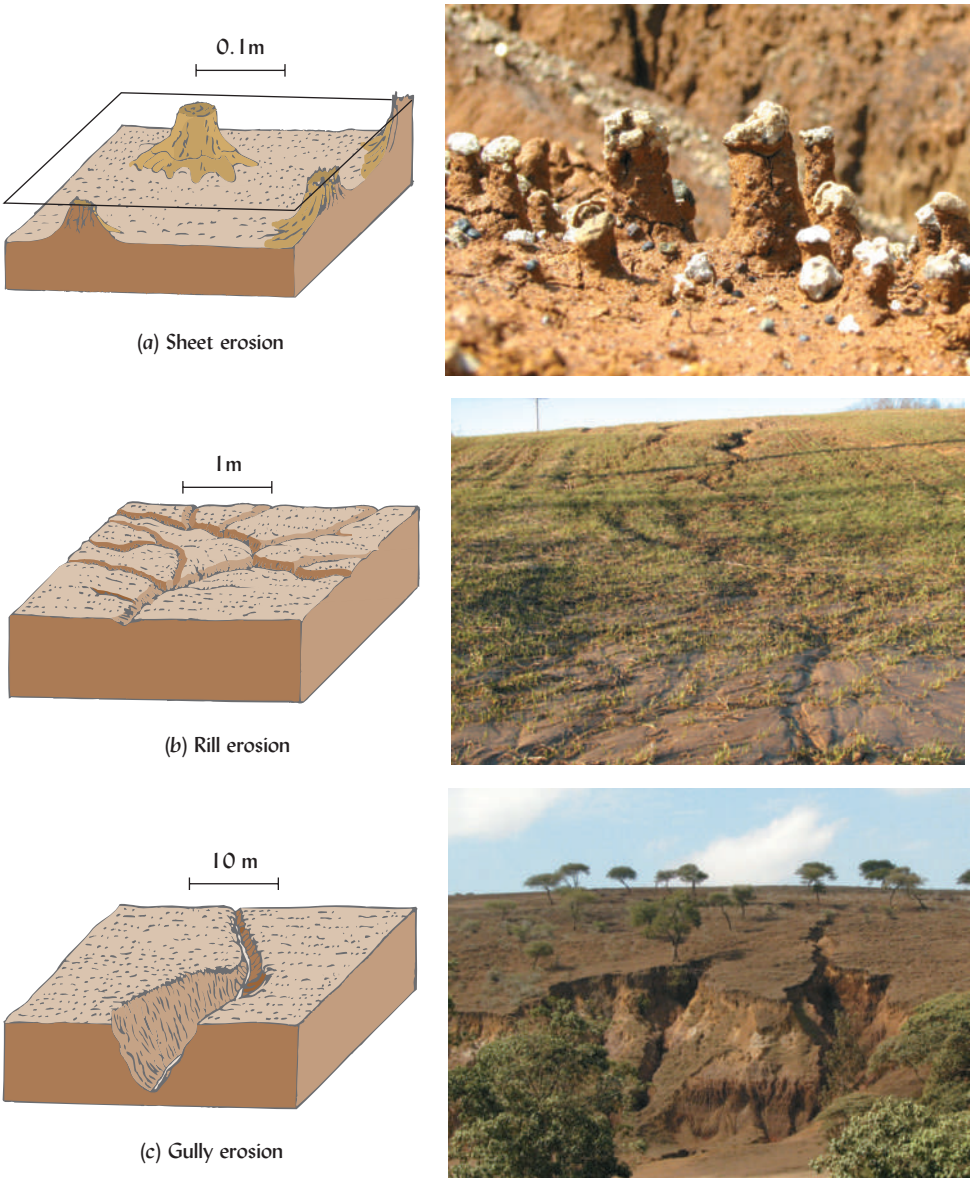

Figure 17.10 *Three major types of soil erosion. (a)* Sheet erosion *is relatively uniform erosion from the entire soil surface. Note that the small stones have protected the soil underneath them from sheet erosion creating the soil pedestals on which they are perched. (b)* Rill erosion *is initiated when the water concentrates in small channels (rills) as it runs off the soil. Subsequent cultivation may erase rills, but it does not replace the lost soil. (c)* Gully erosion *creates deep channels that cannot be erased by cultivation. Although gully erosion looks the most catastrophic of the three, far more total soil is lost by the less obvious sheet and rill erosion.* [Drawings from FAO (1987); photos courtesy Ray R. Weil]

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rill erosion becomes dominant. Rills are especially common on bare land, whether newly planted or in fallow (see Figure 17.10*b*). Rills are channels small enough to be smoothed by normal tillage, but the damage is already done—the soil is lost. When sheet erosion takes place primarily between irregularly spaced rills, it is called **interrill erosion**.

Where the volume of runoff is further concentrated, the rushing water cuts deeper into the soil, deepening and coalescing the rills into larger channels termed **gullies** (see Figure 17.10*c*). This is **gully erosion**. Gullies on cropland are obstacles for tractors and cannot be removed by ordinary tillage practices. All three types may be serious, but sheet and rill erosion, although less noticeable than gully erosion, are responsible for most of the soil moved.

Deposition of Eroded Soil

Erosion may send soil particles on a journey of a thousand kilometers or more—off the hills, into creeks, and down great muddy rivers to the ocean. On the other hand, eroded soil may travel only a meter or two before coming to rest in a slight depression on a hillside or at the foot of a slope (as was shown in Figure 17.6). The amount of soil delivered to a stream, divided by the amount eroded, is termed the **delivery ratio**. As much as 60% of eroded soil may reach a stream (delivery ratio = 0.60) in certain watersheds where valley slopes are very steep. As little as 1% may reach the streams draining a gently sloping coastal plain. Typically, the delivery ratio is larger for small watersheds than for large ones, because the latter provide many more opportunities for deposition before a major stream is reached. It is estimated that about 5–10% of all eroded soil in North America is washed out to sea. The remainder is deposited in reservoirs, river beds, on flood plains, or on relatively level land farther up the watershed.

17.4 MODELS TO PREDICT THE EXTENT OF WATER-INDUCED EROSION

Land managers and policymakers have many reasons to seek ways to predict the extent of soil erosion under different circumstances:

1. To plan for the best management of a nation's soil resources
2. To evaluate the consequences of alternative tillage practices on a farm
3. To determine compliance with environmental regulations
4. To develop sediment-control plans for construction projects
5. To estimate the years it will take to silt-in a hydroelectric dam or reservoir.

The detachment, transport, and deposition processes of soil erosion can be predicted mathematically by soil erosion *models.* These are equations—or sets of linked equations—that interrelate information about the rainfall, soil, topography, vegetation, and management of a site with the amount of soil likely to be lost by erosion.

The Water Erosion Prediction Project (WEPP)[7]

One of the most ambitious and sophisticated erosion models developed so far is a complex, process-based computer program called the WEPP. It is based on an understanding of the fundamental mechanisms involved with each process leading to soil erosion.

WEPP is a *simulation* model that computes, on a daily basis, the rates of hydrologic, plant-growth, and even litter-decay processes. Theoretically, it can predict exactly how rainfall will interact with the soil on a site during a particular rainstorm or during the course of an entire year. If sufficient data are available to feed into the model, it can predict both on-site and off-site effects of raindrop impact, splash erosion, interrill flow, rill formation, channelization, gully formation, and sediment deposition. Currently, researchers with the USDA, along with others throughout the world, continue to compile the necessary databases, test and improve the WEPP model, and make it accessible via the Internet.

[7]The WEPP computer model program, supporting instructions and associated databases can be downloaded freely from: http://www.ars.usda.gov/Research/docs.htm?docid=10621. The WEPP model was developed over a 30-year period and continues to be updated and improved (Flanagan et al., 2007).

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The Soil and Water Assessment Tool (SWAT)[8]

The SWAT is a widely used computer model with even greater complexity and a broader scope than WEPP. The SWAT combines many individual computer models into a large complex "super model" capable of simulating many hydrologic processes within large heterogeneous watersheds. In addition to simulating soil erosion and sediment transport, SWAT also can simulate surface and subsurface runoff, stream flows, groundwater recharge, and the movement of nutrients (N and P) in association with sediment or dissolved in water. It is designed to predict how regional soil erosion, sediment loads, and quality and quantity of surface and ground water will respond to changes in land management and climate. In calculating the loss of sediment by soil erosion, the SWAT uses a subroutine of equations based on a modified universal soil loss equation (MUSLE), a modification of an older, simpler empirical erosion model, which we will describe next. For small watersheds, both the WEPP and the SWAT can be used to predict sediment and runoff losses with reasonable accuracy. However, when predictions from either model are compared with actual in-field measurements it can be seen that while both models are quite good, they carry a certain level of uncertainty, with neither model always providing a close match to reality (e.g., Figure 17.11).

The Universal Soil-Loss Equation (USLE)[9]

In contrast to the process-based operation of WEPP, most predictions of soil erosion continue to rely on much simpler models that statistically relate soil erosion to a number of easily observed environmental factors. Scientists can make such *empirical* models if they know that certain conditions are associated with soil erosion, even if they do not understand the details of *why* this is so. At the heart of these models is the realization that water-induced erosion results from the interaction of rain and soil. More than half a century of erosion research have clearly identified the major factors affecting this interaction. These factors are quantified in the **USLE**:

$$A = R \times K \times LS \times C \times P \tag{17.1}$$

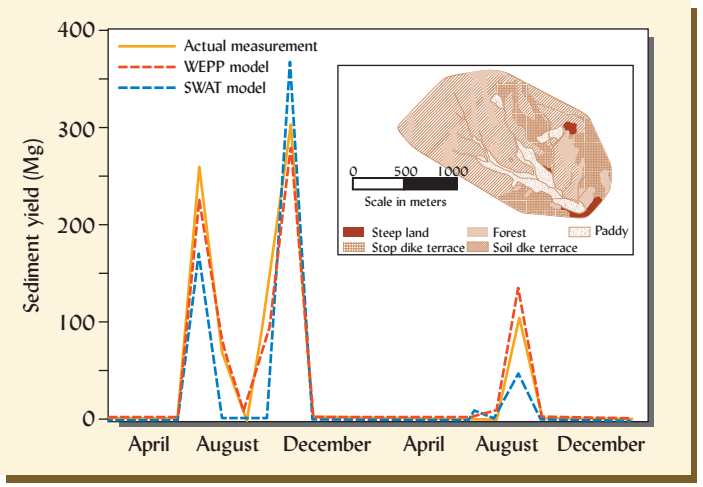

Figure 17.11 *A test of the ability of WEPP and SWAT erosion models to predict actual measured sediment yield from a small subwatershed in China's Three Gorges Dam project. For both models the watershed was broken up into the five land classes shown in inset map. The results from WEPP appeared to more closely predict the actual measurements than did SWAT, but considerable uncertainty remains with both models.* [Diagram based on figures in Shen et al. (2009)]

[8]The SWAT is a public domain model designed to simulate the physical processes governing water runoff and erosion from small to regional watersheds. It can be downloaded for free and is supported by extensive documentation online and has been applied to erosion and hydrological issues around the world (Gassman et al., 2014; USDA/ARS, 2014).

[9]For discussion of the original USLE, see Wischmeier and Smith (1978), and for the RUSLE, see Renard et al. (1994). In this textbook, we use the scientifically acceptable SI units for the *R* and *K* factors in our discussion of these erosion equations.

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A, the predicted annual soil loss, is the product of

R = rainfall erosivity	Rain-related factor
K = soil erodibility L = slope length S = slope gradient or steepness	Soil-related factors
C = cover and management P = erosion-control practices	Land-management factors

Working together, these factors determine how much water enters the soil, how much runs off, how much soil is transported, and when and where it is redeposited. Note that because the factors are multiplied together, *if any one factor could be reduced to zero, the resulting amount of erosion (A) would also be reduced to zero*. More details about the erosion factors are given in Table 17.3.

Unlike the WEPP and SWAT programs, the USLE was designed to predict only the amount of soil loss by sheet and rill erosion in an average year for a given location. It cannot predict erosion from a specific year or storm, nor can it predict the extent of gully erosion and sediment delivery downslope or to streams. It can, however, show how varying any combination of the soil- and land-management-related factors might be expected to influence soil erosion, and therefore can be used as a decision-making aid in choosing the most effective strategies to conserve soil.

Table 17.3
SUMMARY OF MAJOR DIFFERENCES BETWEEN USLE AND RUSLE

Factor	Universal soil-loss equation (USLE)	Revised universal soil-loss equation (RUSLE)
R	Based on long-term average rainfall conditions for specific geographic areas.	Generally the same as USLE but averages may be based on data from more weather stations and are more precise for specific locations. RUSLE computes a correction to *R* for flat land to reflect the effect of raindrop impact on ponded water.
K	Based on soil texture, organic matter content, permeability, and other factors inherent to soil type.	Same as USLE but adjusted to account for seasonal changes, such as freezing and thawing, soil moisture, and soil consolidation.
LS	Based on length and steepness of slope, regardless of land use.	Refines USLE by considering complex slopes and the ratio of rill to interrill erosion.
C	Based on cropping sequence, surface residue, surface roughness, and canopy cover, which are weighted by the percentage of erosive rainfall during six crop stages. Lumps these factors into a table of soil-loss ratios, by crop and tillage scheme.	Uses these subfactors: prior land use, canopy cover, surface cover, surface roughness, and soil moisture. Refines USLE by calculating the soil-loss ratio for each 15-day interval in the year. Recalculates a new soil-loss ratio every time a tillage operation changes one of the subfactors. RUSLE provides improved estimates of soil-loss as changes in residue and canopy cover occur throughout the year.
P	Based on installation of practices that slow runoff and thus reduce soil movement. *P* factor values change according to slope ranges with some distinction for various ridge heights.	*P* factor values are based on hydrologic soil groups, slope, row grade, ridge height, the amount and location of deposition and the ten-year single storm erosion index value. The effect of strip-cropping based on the transport capacity of flow in dense strips relative to the amount of sediment reaching the strip.

Based on Renard et al. (1994).

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The Revised Universal Soil-Loss Equation (RUSLE)

The USLE has been used widely since the 1970s. Beginning in the 1990s, the basic USLE was updated and computerized to create an erosion-prediction tool called the **RUSLE**. The RUSLE uses the same basic factors of the USLE just shown, although some are better defined, and interrelationships between them improve the accuracy of soil-loss prediction. The RUSLE is a computer software package that is constantly being improved and modified as experience is gained from its use around the world. The major differences between USLE and RUSLE are listed in Table 17.3.

As we are about to see, the five factors that comprise the USLE provide a useful framework for understanding soil erosion by water and its control.

17.5 FACTORS AFFECTING INTERRILL AND RILL EROSION

Rainfall Erosivity Factor *R*

The rainfall **erosivity** factor *R* represents the driving force for sheet and rill erosion. It takes into consideration the total rainfall and, more important, the intensity and seasonal distribution of the rain. Rain intensity is of great importance for two reasons: (1) intense rains have a large drop size, which results in much greater kinetic energy being available to detach soil particles; and (2) the higher the rate of rainfall, the more runoff that occurs, providing the means to transport detached particles. Gentle rains of low intensity may cause little erosion, even if the total annual precipitation is high. In contrast, a few torrential downpours may result in severe damage, even in areas of low annual rainfall. Likewise, soil losses are heavy if the rain falls when the soil is just thawing or is relatively bare because of recent disturbance.

An index of the kinetic energy of each storm is calculated from data related to the intensity and amount of rainfall. Then the indices for all storms occurring during a year are summed to give an annual index. An average of such indexes for many years is used as the *R* value in the universal soil-loss equation. The RUSLE includes more precise values (Table 17.3).

Rainfall index values for locations in the United States are shown in Figure 17.12. Note that they vary from less than 400 in areas of the west to more than 10,000 along the coasts of Louisiana, USA [the map gives *R* values in SI units of (MJ · mm)/(ha · h · yr) that can be converted to English units if divided by 17.02]. Similar maps have been generated in other parts of the world. Generally, rainfall tends to be more intense and more erosive in subtropical and tropical regions than in temperate regions.

Rainfall intensity in most locations is so highly variable that actual erosivity in any one year is commonly 2–5 times greater or smaller than the long-term average. In fact, a few unusually intense, heavy storms often account for most of the erosion that takes place (Figure 17.13). Conservation practices based on the predictions of the USLE or RUSLE using long-term average *R* factors may not be sufficient to limit erosion damages from these relatively rare, but extremely damaging, storms.

Soil Erodibility Factor *K*

The soil **erodibility** factor *K* indicates a soil's inherent susceptibility to erosion. The *K* value assigned to a particular type of soil indicates the amount of soil lost per unit of erosive energy in the rainfall, assuming a standard research plot (22 m long, 9% slope) on which the soil is kept continuously bare by tillage.

The two most significant and closely related soil characteristics influencing erodibility are: (1) *infiltration capacity* and (2) *structural stability.* High infiltration means that less water will be available for runoff, and the surface is less likely to be ponded (which would make it more susceptible to splashing). Stable soil aggregates resist the beating action of rain, and resist soil detachment even though runoff may occur. Certain tropical clay soils high in hydrous oxides of iron and aluminum are known for their highly stable aggregates that resist the action of torrential rains. Downpours of a similar magnitude on swelling-type clays would be disastrous.

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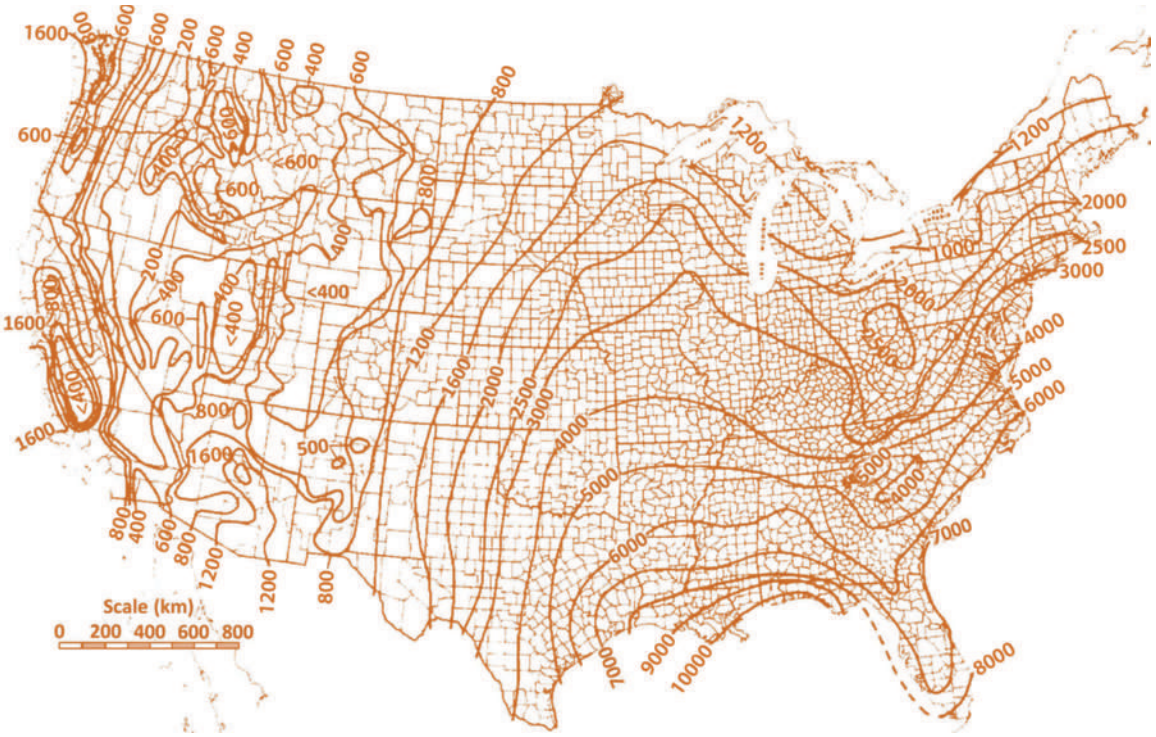

Figure 17.12 *The geographic distribution of* R *values for rainfall erosivity in the continental United States. Note the very high values in the humid, subtropical Southeast, where annual rainfall is high and intense storms are common. Similar amounts of annual rainfall along the coast of Oregon and Washington in the Northwest result in much lower* R *values because there the rain mostly falls gently over long periods. The complex patterns in the West are mainly due to the effects of mountain ranges. Values on map are in units of (MJ·mm)/(ha·h·yr). To convert to English units of 100 (ft·ton·in.)/(acre·yr), divide by 17.02.* [Redrawn from USDA (1995)]

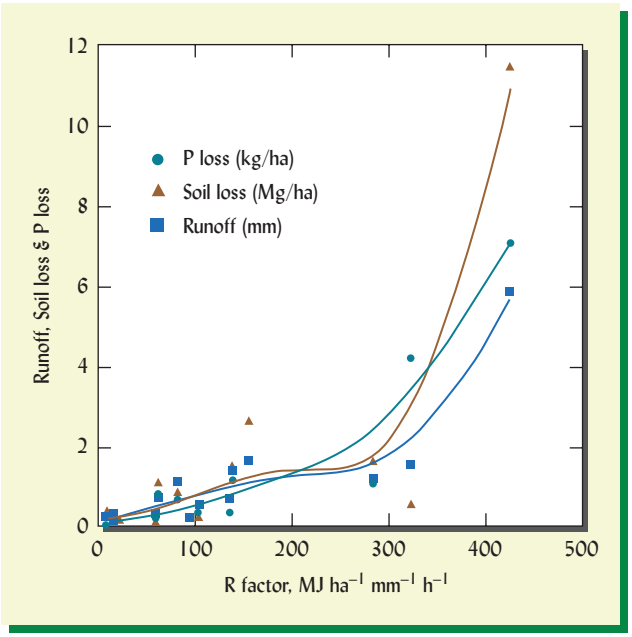

Figure 17.13 *Influence of the R factor (rainfall energy) on runoff water, soil loss, and phosphorus runoff loss in a vineyard in northeastern Spain. The vineyard had been leveled prior to planting the grape vines and the soil exposed at the surface was very low in organic matter. The data are based on measurements during 17 natural rainfall events over a three-year period. The study results illustrate that most soil and nutrient losses result from a small number of extreme events.* [Graph based on data selected from Ramos and Martinez-Casasnovas (2006)]

Basic soil properties that tend to result in high *K* values include high contents of silt and very fine sand; expansive types of clay minerals; a tendency to form surface crusts; the presence of impervious soil layers; and blocky, platy, or massive soil structure. Soil properties that tend to make the soil more *resistant to erosion* (low *K* values) include high soil organic matter content, nonexpansive types of clays, and strong granular structure. Approximate *K*

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values for soils at selected locations are shown in Table 17.4. Such tabular *K* values assigned to particular soil series do not account for possible impacts, positive or negative, of prior soil management.

Site-specific *K* values obtained with the RUSLE program will vary somewhat from these values. Note that the *K* factor in SI units normally varies from near zero to about 0.1. Soils with high rates of water infiltration commonly have *K* values of 0.025 or below, while more easily eroded soils with low infiltration rates have *K* factors of 0.04 or higher.

Unlike the USLE, the RUSLE takes into account the fact that *K* values vary seasonally. For example, in cold regions, thawing of frozen soil in spring results in higher *K* values, because the soil is supersaturated with water and is "fluffy" from freeze–thaw action. Also, the *K* factor in RUSLE may be reduced with time in stony soils, because they become protected by an armor of stone fragments left on the soil surface after the finer soil components erode away.

Topographic Factor *LS*

The topographic factor *LS* reflects the influence of length and steepness of slope on soil erosion. It is expressed as a unitless ratio with soil loss from the area in question in the numerator, and that from a standard plot (9% slope, 22 m long) in the denominator. The longer the slope, the greater the opportunity for accumulation and concentration of the runoff water.

Figure 17.14 illustrates the increases in *LS* factors that occur as slope length and steepness increase. Three graph panels are given for sites with low, moderate, and high ratios of rill to interrill (sheet) erosion. Most sites cultivated to row crops have moderate rill to interrill erosion ratios. On sites where this ratio is low, such as rangelands, more of the soil movement occurs by interrill erosion. On these sites, slope steepness (%) has a relatively greater influence on erosion, while the slope length has a relatively smaller influence. The opposite is true for

Table 17.4
COMPUTED *K* VALUES FOR SOILS AT DIFFERENT LOCATIONS
The values listed are in SI units. Values in the RUSLE program may differ somewhat.

Soil	Location	Compounds[a] *K*
Udalf (Dunkirk silt loam)	Geneva (New York, USA)	0.091
Udalf (Keene silt loam)	Zanesville (Ohio, USA)	0.063
Udult (Lodi loam)	Blacksburg (Virginia, USA)	0.051
Udult (Cecil sandy clay loam)	Watkinsville (Georgia, USA)	0.048
Udoll (Marshall silt loam)	Clarinda (Iowa, USA)	0.044
Udalf (Hagerstown silty clay loam)	State College (Pennsylvania, USA)	0.041
Ustoll (Austin silt)	Temple (Texas, USA)	0.038
Aqualf (Mexico silt loam)	McCredie (Missouri, USA)	0.034
Udult (Cecil sandy loam)	Watkinsville (Georgia, USA)	0.030
Alfisols	Indonesia	0.018
Oxisols	Ivory Coast	0.013
Udult (Tifton loamy sand)	Tifton (Georgia, USA)	0.013
Ultisols	Hawaii, USA	0.012
Alfisols	Nigeria	0.008
Udept (Bath flaggy silt loam)	Arnot (New York, USA)	0.007
Ultisols	Nigeria	0.005
Oxisols	Puerto Rico	0.001

[a]To convert these *K* values from (Mg · ha · h)/(ha · MJ · mm) to English units of (ton · acre · h)/(100 acres · ft-ton · in.), simply multiply the values in this table by 7.6. From Wischmeier and Smith (1978); data for tropical soils cited by Cassel and Lal (1992).

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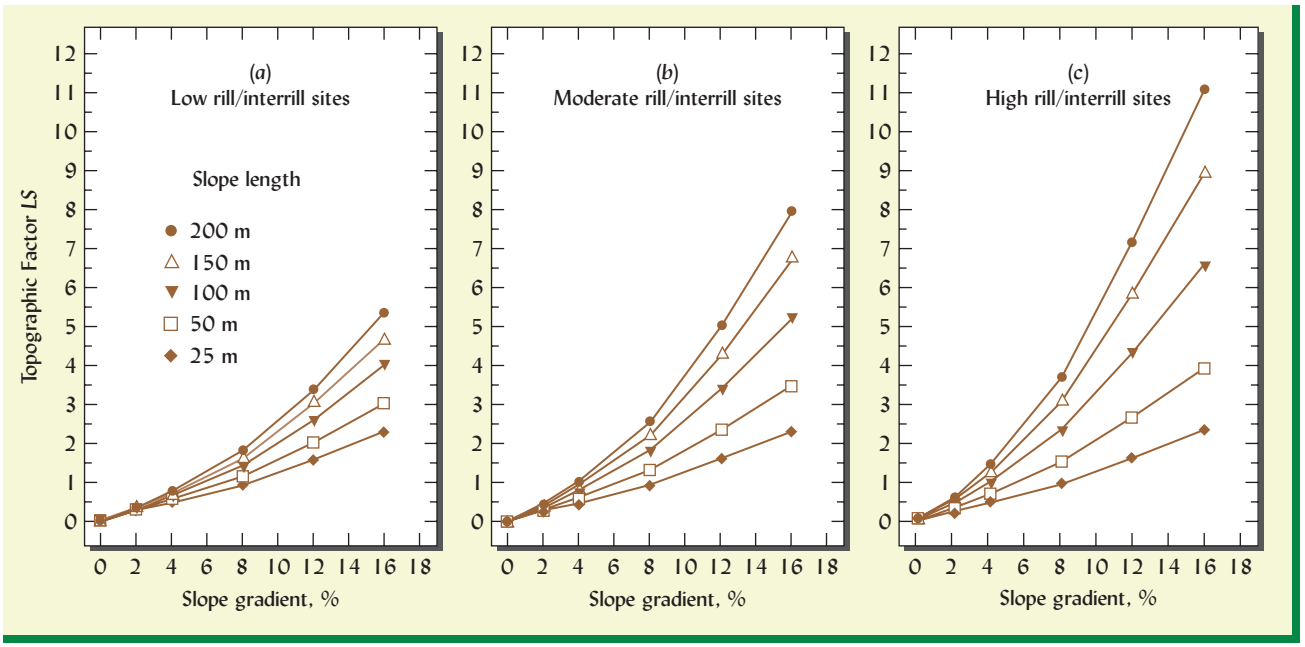

Figure 17.14 *Relationship between values of the topographic factor* LS *and the slope gradient for several lengths of slope on three types of sites: (a) sites with low ratios of rill to interrill erosion, such as many rangelands; (b) sites with moderate ratios of rill to interrill erosion, such as most tilled row-crop land; and (c) sites with high ratios of rill to interrill erosion, such as freshly disturbed construction sites and new seedbeds. The* LS *values extrapolated from these graphs can be used in the Universal Soil-Loss Equation.* [Graphs based on data in Renard et al. (1994)]

freshly excavated construction areas and other highly disturbed sites, which have high rill to interrill erosion ratios. Here, where rill erosion predominates, slope length has a greater influence. While such generalized *LS* factor values for simple slopes can be used with the USLE, the RUSLE computer program calculates more location-specific values, including values for complex (nonuniform) slopes.

Cover and Management Factor *C*

Erosion and runoff are markedly affected by different types of vegetative cover or cropping systems (Table 17.5). Undisturbed forests and dense grass (Figure 17.15, *right*) provide the best soil protection and are about equal in their effectiveness. Even in semiarid regions unable

Table 17.5
EFFECT OF PLANT COVER ON SOIL EROSION BY WATER IN THE HUMID ZONE OF WEST AFRICA
Means of many nearby sites, all with similar slopes, soils, and rainfall. The data illustrate the protective effect of undisturbed forest vegetation and the erosive effects of cultivation (with tillage), especially bare fallows.

Type of cover	Number of sites	Mean rainfall, mm/y	Runoff, % of rainfall	Erosion, Mg/ha
Forest protected from fire	11	1293	0.9	0.10
Forest with light fires	13	1289	1.1	0.27
Natural bunchgrass fallow	7	1203	16.6	4.88
Groundnut (peanut)	32	1329	20.7	7.70
Upland rice	17	946	23.3	5.52
Maize (corn)	17	1405	17.7	7.63
Failed crops and bare soil	11	1154	39.5	21.28

Data selected from that cited by Pierre (1992).

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to support dense vegetation, increasing the density of trees and shrubs to cover more than one-third to one-half of the soil surface can dramatically reduce the loss of both soil and water in runoff (Figure 17.16). On agricultural land, forage crops (both legumes and grasses) are most effective in staunching erosion because of their relatively dense cover. Small grains, such as wheat and oats, are intermediate and offer considerable obstruction to surface wash during their growing season. Row crops, such as corn, soybeans, cotton, and potatoes, offer relatively little living cover during the early growth stages and thereby leave the soil susceptible to erosion (Figure 17.15, *left*) unless residues and stubble from previous crops protect the soil surface.

Cover crops consist of plants that are similar to the forage crops just mentioned that are grown primarily to stem soil erosion and improve soil health. They can provide soil protection during the time of year between the growing seasons for annual crops. For widely spaced perennial plantings such as orchards and vineyards, cover crops can permanently protect the soil between rows of trees or vines. A mulch of plant residue or applied materials is also effective in protecting soils. Research on all continents has shown that surface mulch does not have to be very thick or cover the soil completely to make a major contribution to soil conservation.

Figure 17.15 *The importance of vegetative cover on soils. Immediately after a heavy rainstorm, runoff* (left) *is scouring a gully and carrying off a heavy sediment load from a cultivated soil with almost no residue cover while* (right) *on a soil with almost 100% cover the runoff is clear.* (Photos courtesy of Ray R. Weil)

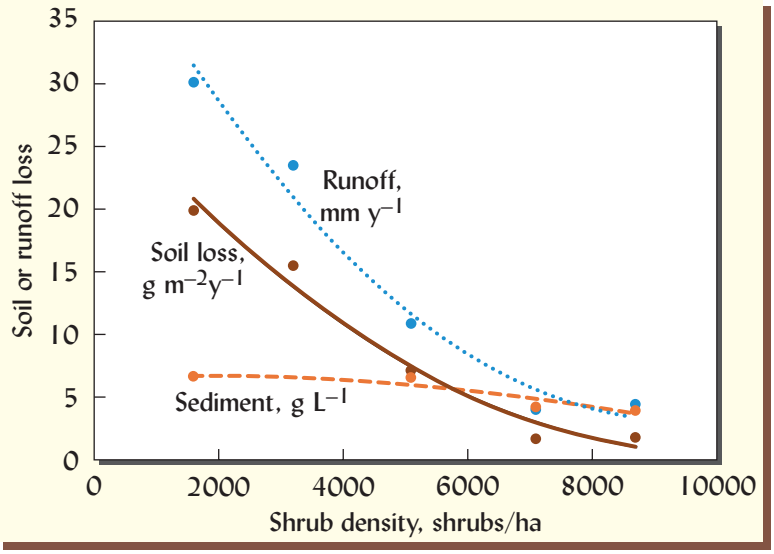

Figure 17.16 *Effect of shrub planting density on runoff and soil erosion in a hilly semiarid loess region in Ningxia province, western China. Deep-rooted, fast-growing shrubs (*Caragana korshinskii *Kom.) were planted for afforestation at densities that achieved canopy cover ranging from 20% to 75%. Both runoff water and soil loss were dramatically reduced by planting more shrubs, but the concentration of sediment in the runoff that did occur was only slightly affected. The Huangmian soil (Haplocalcids) is developed from loess and is highly erodible. The region receives 416 mm of rainfall annually, mainly between June and September.* [Graphed from data in Guo and Shao (2013)]

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Even small increases in surface cover result in large reductions in soil erosion, particularly interrill erosion (Figure 17.17).

Regulation of grazing to maintain a dense vegetative cover on range- and pastureland and the inclusion of close-growing hay crops in rotation with row crops on arable land will help control both erosion and runoff. Likewise, the use of conservation tillage systems, which leave most of the plant residues on the surface, greatly decreases erosion hazards.

The *C* factor in the USLE or RUSLE is the ratio of soil loss under the conditions in question to that which would occur under continuously bare soil. This ratio *C* will approach 1.0 where there is little soil cover (e.g., a bare seedbed in the spring or freshly graded bare soil on a construction site). It will be low (e.g., <0.10) where large amounts of plant residues are left on the land or in areas of dense perennial vegetation.

Values of *C* are specific to each region and type of vegetation or soil management. Estimates based on experiment data and field experience are available from conservation offices and the RUSLE program. Examples of *C* values are given in Table 17.6.

Support Practice Factor *P*[10]

On some sites with long and/or steep slopes, erosion control achieved by management of vegetative cover, residues, and tillage must be augmented by the construction of physical structures or other steps aimed at guiding and slowing the flow of runoff water. These **support practices** determine the value of the *P* factor in the USLE. The *P* factor is the ratio of soil loss with a given support practice to the corresponding loss if row crops were planted up and down the slope. If there are no support practices, the *P* factor is 1.0. The support practices include tillage on the contour, contour strip-cropping, terrace systems, and grassed waterways, all of which will tend to reduce the *P* factor.

Contour Cultivation. Rows of plants slow the flow of runoff water if they follow the contours across the slope gradient (but the rows *encourage* channelization and gullies if they run up and down the slope; Figure 17.18). Even more effective is planting on ridges built up of soil *along the contours*. However, ridges must be designed to carry heavy runoff safely from the field, or else severe erosion may occur when the ridges overflow (Figure 17.19).

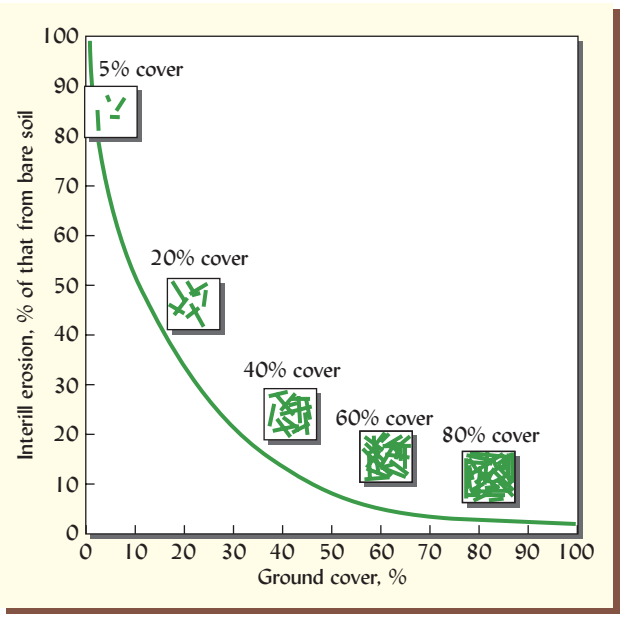

Figure 17.17 *Reduction in interrill erosion achieved by increasing ground cover percentage. The diagrams above the graph illustrate 5%, 20%, 40%, 60%, and 80% ground cover. Note that even a light covering of mulch has a major effect on soil erosion. The graph applies to interrill erosion. On steep slopes, some rill erosion may occur even if the soil is well covered. Generalized relationship based on results from many studies.* (Diagram courtesy of Ray R. Weil)

[10]Many of the erosion-control practices or management techniques discussed with regard to the *C* and *P* factors and in later sections of this chapter are considered to be **best management practices** (**BMPs**) (see also on Section 16.2). In the United States, the Clean Water Act defines BMPs as "optimal operating methods and practices for reducing or eliminating water pollution" from land-use activities.

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Table 17.6
EXAMPLES OF *C* VALUES FOR THE COVER AND VEGETATION MANAGEMENT FACTOR
The C values indicate the ratio of soil eroded from a particular vegetation system to that expected if the soil were kept completely bare. Note the effects of canopy cover, surface litter (residue) cover, tillage, and crop rotation. The C values are site and situation specific and must be calculated from local information on plant growth habits, climate, and so on. Specific values may be obtained from the RUSLE computer program or from local conservation agencies.

Vegetation	Management/condition	*C* value
Range grasses and low (<1 m) shrubs	75% canopy cover, no surface litter	0.17
	75% canopy cover, 60% cover with decaying litter	0.032
Scrub brush about 2 m tall	25% canopy cover, no litter	0.40
	75% canopy cover, no litter	0.28
Trees with no understory, about 4 m drop fall	75% canopy cover, no litter	0.36
	75% canopy cover, 40% leaf litter cover	0.09
	75% canopy cover, 100% leaf litter cover	0.003
Woodland with understory	90% canopy cover, 100% litter cover	0.001
Permanent pasture	Dense grass sod, properly grazed	0.003
Corn–soybean rotation	Fall plowing, conventional tillage, residues removed	0.53
	Spring chisel plow–plant conservation tillage, 2500 kg/ha surface residues after planting	0.22
	No-till planting, 5000 kg/ha surface residues	0.06
	No-till with winter cover crops	0.02
Corn–soybean–wheat–hay rotation	Fall plowing, conventional tillage, residues removed	0.20
	Spring chisel plow–plant conservation tillage, 2500 kg/ha surface residues after planting	0.13
	No-till planting, 5000 kg/ha surface residues after planting	0.05
Corn–oats–hay–hay rotation	Spring conventional plowing before planting	0.05
	No-till planting	0.03

Values typical of Midwestern United States. Based on Wischmeier and Smith (1978) and Schwab et al. (1996).

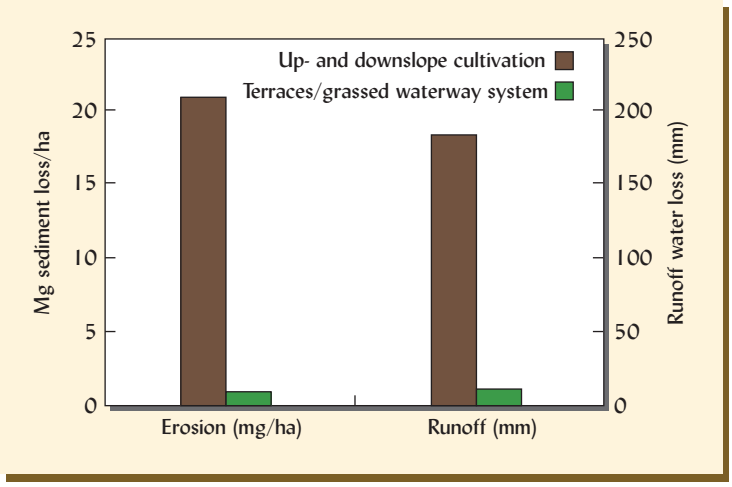

Figure 17.18 *Erosion and water runoff losses from small watersheds where potato (a row crop with high soil disturbance) was grown either up and down the slope, or on the contour in a system with diversion terraces and a grassed waterway. The contour practices provided dramatic soil and water conservation benefits. Data are annual rates averaged across three years.* [From Chow et al. (1999)]

On long slopes subject to sheet and rill erosion, fields may be laid out in narrow strips across the incline, alternating the tilled row crops, such as corn, soybean, or potato, with hay and small grains (such as wheat or barley). Water cannot achieve an undue velocity on the narrow strips of tilled land, and the hay and small grain crops check the rate of runoff. Such a

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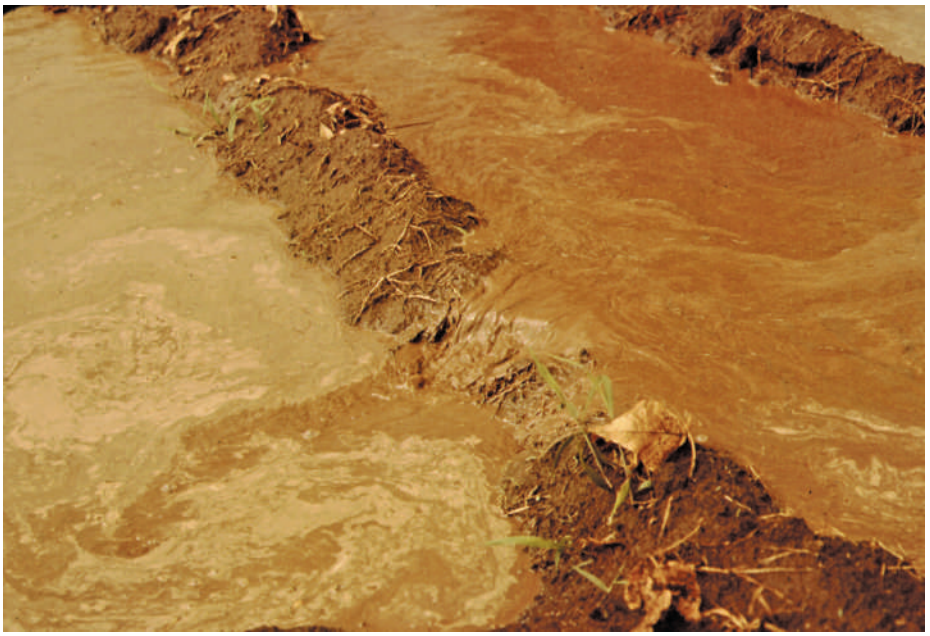

Figure 17.19 *Contour ridges on a clean-tilled crop field impacted by heavy rain just before the crop was planted. Such ridges can reduce runoff losses and increase infiltration. However, they must be carefully laid out so as to provide sufficient slope (usually 0.5% off the true contours) to allow rainfall in excess of the infiltration rate to safely runoff the field rather than accumulate at low spots and overtop the ridges as seen here.* (Photo courtesy of Ray R. Weil)

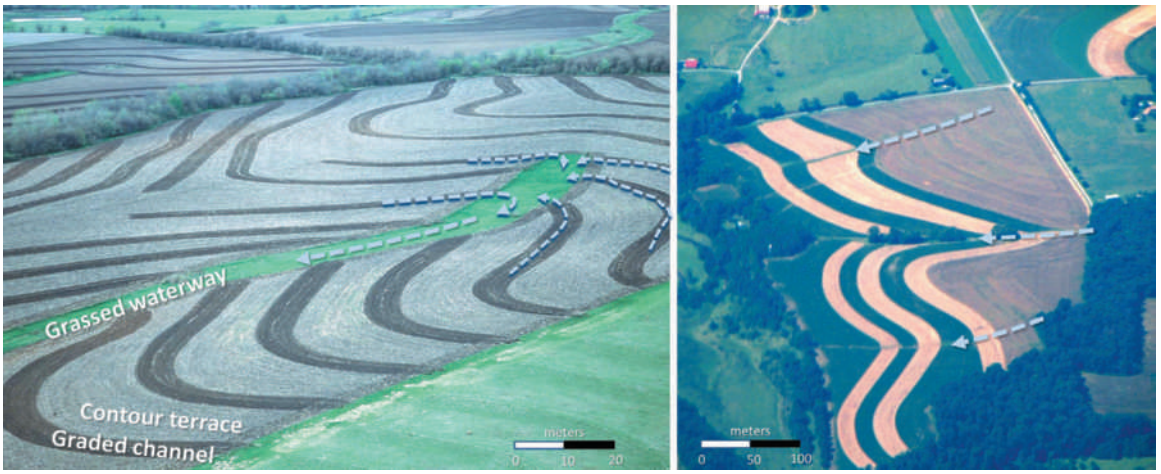

Figure 17.20 *Practices supporting erosion control.* (Left) *Contour cropping with* graded terraces *between crop strips and grassed waterway to safely convey off excess water off a sloping field in Kansas, USA. The broken arrows show paths taken by the runoff water.* (Right) Contour strip-cropping *with alternating strips of mature wheat and young green alfalfa on a farm in New York, USA. The arrow indicates a grassed waterway.* (Photos courtesy of Jeff Vanuga, USDA/NRCS (*left*) and Ray R. Weil (*right*))

layout is called **strip-cropping** and is the basis for erosion control in many hilly agricultural areas. This arrangement can be thought of as shortening the effective slope length.

When the cross strips are laid out to approximately follow the slope contours, the system is called **contour strip-cropping** (Figure 17.20). The width of the strips will depend primarily on the slope steepness and the soil permeability and erodibility. Widths of 20–120 m are common. Contour strip-cropping is often augmented by diversion ditches and waterways between fields. Permanent sod established in the swales produces **grassed waterways** that can safely carry water off the land without the formation of gullies (see Figure 17.21, *right*).

Terraces. Construction of various types of terraces reduces the effective length and gradient of a slope (Figure 17.20, *left*). **Bench terraces** are used where nearly complete control of the water runoff must be achieved, such as in rice paddies (see Figure 6.45). Where farmers use large machinery and need to farm all the land in a field, **broad-based terraces** are more

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Figure 17.21 *Concentrated runoff erodes soil and carries away sediments on an unprotected, conventionally tilled crop field, despite planting across the slope (*left*). Water runs clear without scouring soil from a crop field protected by a permanent grassed waterway (*right*).* (Photos courtesy of USDA/NRCS)

common. Broad-based terraces waste little or no land and are quite effective if properly maintained. Water collected behind each terrace flows gently across (rather than down) the field in a terrace channel, which has a drop of only about 50 cm in 100 m (0.5%). The terrace channels should guide the runoff water to grassed waterways (Figures 17.20 and 17.21), so that the runoff water can move downhill off the field to a nearby stream or drainage canal.

Examples of P values for contour tillage and strip-cropping at different slope gradients are shown in Table 17.7. Note that P values increase with slope and that they are lower for strip-cropping, illustrating the importance of this practice for erosion control. Terracing also reduces the P values. Unlike the USLE, the RUSLE takes into account interactions between support practices and subfactors such as slope and soil water infiltration.

The five factors of the USLE (R, K, LS, C, and P) have suggested many approaches to the practical control of soil erosion. A sample calculation is shown in Box 17.1 to illustrate how the USLE can help evaluate erosion-control options.

While we have just discussed mainly erosion from agricultural land, erosion by water also needs to be controlled on forests, rangeland, and construction sites. We will now focus on several specific erosion-control technologies appropriate for various types of land uses.

17.6 CONSERVATION TILLAGE[11]

For centuries, conventional agricultural practice around the world has encouraged extensive soil tillage that leaves the soil bare and unprotected from the ravages of erosion. Beginning in the middle of the twentieth century, two technological developments allowed many farmers to avoid this problem by managing their soils with little tillage—or no tillage at all. First came the development of herbicides that could kill weeds chemically without tillage. Second, farmers and equipment manufacturers developed machinery that could plant crop seeds even if the soil was in an unloosened state and covered by plant residues. These developments obviated two of the main reasons that farmers till their soils. Farmer interest in reduced tillage heightened as it was shown that these systems produced equal or even higher crop yields in many regions while saving time, fuel, money—and soil. The latter attribute earned these systems the name of **conservation tillage**. More recently, organic farmers and researchers who do not use chemical herbicides have worked to develop practical systems of conservation tillage that use cover crops to suppress weeds while reducing the amount of tillage performed (see Section 16.2).

[11]For a review of conservation tillage technology, see Carter (1994). For a review of economic and policy considerations for conservation agriculture, see FAO (2001).

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Table 17.7
P FACTORS FOR CONTOUR AND STRIP-CROPPING AT DIFFERENT SLOPES AND THE TERRACE SUBFACTOR AT DIFFERENT TERRACE INTERVALS
The product of the contour or strip-cropping factors and the terrace subfactor gives the P value for terraced fields.

				Terrace subfactor	
Slope, %	Contour *P* factor	Strip-cropping *P* factor	Terrace interval, m	Closed outlets	Open outlets
1–2	0.60	0.30	33	0.5	0.7
3–8	0.50	0.25	33–44	0.6	0.8
9–12	0.60	0.30	43–54	0.7	0.8
13–16	0.70	0.35	55–68	0.8	0.9
17–20	0.80	0.40	69–60	0.9	0.9
21–25	0.90	0.45	90	1.0	1.0

Contour and strip-cropping factors from Wischmeier and Smith (1978); terrace subfactor from Foster and Highfill (1983).

BOX 17.1

CALCULATIONS OF EXPECTED SOIL LOSS USING USLE

The RUSLE computer software is designed to calculate the expected soil loss from specific cropping systems at a given location.

The principles involved in both USLE and RUSLE can be verified by making calculations using USLE and its associated factors. Note that the factors in the USLE are related to each other in a multiplicative fashion. Therefore, if any one factor can be made to be near zero, the amount of soil loss *A* will be near zero.

Assume, for example, a location in Iowa on a Marshall silt loam with an average slope of 6% and an average slope length of 100 m. Assume further that the land is clean-tilled and fallowed.

Figure 17.12 shows that the *R* factor for this location is about 2550 in SI units (150 in English units, 2550/17 = 150). The *K* factor for a Marshall silt loam in central Iowa is 0.044 (Table 17.4) and the topographic factor *LS* from Figure 17.14 is 1.7 (high rill to interrill ratio on soil kept bare). The *C* factor is 1.0, since there is no cover or other management practice to discourage erosion. If we assume the tillage is up and down the hill, the *P* value is also 1.0. Thus, the anticipated soil loss can be calculated by the USLE ($A = RKLSCP$):

$$A = (2550)(0.044)(1.7)(1.0)(1.0)$$
$$= 191 \text{ Mg/ha [or 85.2 tons/acre]}$$

If the crop rotation involved corn–soybean–wheat–hay and conservation tillage practices (e.g., spring chisel plow tillage) were used, a reasonable amount of residue would be left on the soil surface. Under these conditions, the *C* factor may be reduced to about 0.13 (Table 17.6). Likewise, if the tillage and planting were done on the contour, the *P* value would drop to about 0.5 (Table 17.7). *P* could be reduced further to 0.4 (0.5×0.8) if terraces with open outlets were installed about 40 m apart. Furthermore, with crops on the land the site would have a moderate rill to interrill erosion ratio, so the *LS* factor would be only 1.4 (middle of Figure 17.14). With these figures the soil loss becomes:

$$A = (2550)(0.044)(1.4)(0.13)(0.4)$$
$$= 8.2 \text{ Mg/ha [or 3.4 tons/acre]}$$

The units for the calculation are not normally shown, but they are:

$$\frac{\text{MJ} \cdot \text{mm}}{\text{ha} \cdot \text{h} \cdot \text{yr}} \times \frac{\text{Mg} \cdot \text{ha} \cdot \text{h}}{\text{ha} \cdot \text{MJ} \cdot \text{mm}}$$
$$= \frac{\text{Mg}}{\text{ha} \cdot \text{yr}} \text{ (}LS\text{, }C\text{, and }P\text{ are unitless ratios.)}$$

The benefits of good cover and management and support practices are obvious. The figures cited were chosen to provide an example of the utility of the universal soil-loss equation, but calculations can be made for any specific location. In the United States, pertinent factor values that can be used for erosion prediction in specific locations are generally available from state offices of the USDA Natural Resource Conservation Service. The necessary factors are also built into the RUSLE software which is freely available online.

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Conservation Tillage Systems

While there are numerous conservation tillage systems in use today (Table 17.8), all have in common that they leave significant amounts of organic residues on the soil surface after planting. Keep in mind that conventional tillage involves first moldboard plowing (Figure 17.22, *left*) to completely bury weeds and residues, followed by one to three passes with a harrow to break up large clods, then planting the crop, and subsequently several cultivations between crop rows to kill weeds. Every pass with a tillage implement bares the soil anew and also weakens the structure that helps soil resist water erosion.

Conservation tillage systems range from those that merely reduce excess tillage to the no-tillage system, which does not use any tillage beyond the slight soil disturbance that occurs as the planter cuts a planting slit through the residues to a depth of several cm into the soil (Figure 17.23, *inset*). The conventional moldboard plow was designed to leave the field "clean"; that is, free of surface residues. In contrast, conservation tillage systems, such as **chisel plowing** (Figure 17.22, *right*), stir the soil but only partially incorporate surface residues, ideally leaving more than 30% of the soil covered. **Stubble mulching**, whose water-conserving attributes were highlighted in Section 6.4, is another example. **Ridge tillage** is a conservation system in which crops are planted on top of permanent 15- to 20-cm-high ridges. About 30% soil coverage is maintained, even though the ridges are scraped off a bit for planting and then built up again by shallow tillage to control weeds.

With **no-till** systems (sometimes referred to as *direct seeding*) we can expect 50–100% of the surface to remain covered (Table 17.9). Well-managed continuous no-till systems in humid regions include cover crops during the winter and high-residue-producing crops in the rotation. Such systems keep the soil completely covered at all times and build up organic surface layers somewhat like those found in forested soils.

Conservation tillage systems generally provide yields similar to those from conventional tillage, provided the soil is not too poorly drained and the climate is not too cold. In dry climates or dry years, no-till often out-yields conventional tillage because water as well as soil is

Table 17.8
General Classification of Different Conservation Tillage Systems
To be considered conservation tillage, a system must maintain enough plant residues on the soil to cover at least 30% of the ground surface area after planting.

Tillage system	Operation involved
No-till	Soil undisturbed prior to planting. Seeds placed in narrow slots cut through residues and soil. Slot is closed so only 1–10% of soil surface exposed. Weed control usually by herbicides and/or cover crop residue mulch.
Vertical/turbo till	High speed, shallow disturbance implements with two gangs of forward-facing rolling blades, either straight or waved, spaced about 20–25 cm apart set to disturb vertical slices of soil about 5 cm wide and 4–8 cm deep, as well as chop up surface residues.
Ridge till (till, plant)	Soil undisturbed prior to planting, which is done on ridges 10–15 cm higher than row middles. Residues moved aside or incorporated on about one-third of soil surface. Herbicides and cultivation to control weeds.
Strip till	Soil undisturbed prior to planting. Narrow and shallow tillage in rows using rotary tiller, in-row chisel, etc. About 25–50% of soil surface is tilled at planting time. Herbicides and cultivation to control weeds.
Mulch till	Soil surface disturbed by tillage prior to planting, but at least 30% of ground is covered with residue. Tools such as chisels, field cultivators, disks, and sweeps are used (e.g., stubble mulch). Herbicides and cultivation to control weeds.
Reduced till	Any other tillage and planting system that keeps at least 30% of the soil surface covered by residues.

Definitions, except vertical till, modified from Conservation Technology Information Center, West Lafayette, Ind.

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Figure 17.22 *Conventional inversion tillage and conservation tillage in action.* (Left) *In conventional tillage, a moldboard plow inverts the upper soil horizon, burying all plant residues and producing a bare soil surface.* (Right) *A chisel plow, one type of conservation tillage implement, stirs the soil but leaves a good deal of the crop residues on the soil surface.* (Photos courtesy of Ray R. Weil)

Figure 17.23 *In no-till systems, one crop is planted directly into the residue of a cover crop or of a previous cash crop, with only a narrow band of soil disturbed. No-till systems leave virtually all of the residue on the soil surface, providing up to 100% cover and nearly eliminating erosion losses. Here corn was planted into a cover crop killed with a herbicide (weed-killing chemical) to form a surface mulch. The inset shows a close-up of a no-till planter in action (direction of travel is to the right). The rolling furrow openers cut a slot through the residue and soil into which the seed is placed at a depth set by the depth wheel. Snug seed-to-soil contact is ensured by the press wheel that closes the slot.* (Photos courtesy of Ray R. Weil)

conserved. However, during the transition from conventional tillage to no-tillage, crop yields may decline somewhat for several years for reasons associated with some of the effects outlined in the following subsections.

Adaptation by Farmers[12]

In recent years conservation tillage has become increasingly popular. In the United States, about two-fifths of the nation's cropland is managed with some form of conservation tillage. Conservationists project that as much as 60% of the cropland in the United States will be managed

[12]For the inspiring story of one Chilean farmer's struggle to conquer the forces of erosion and degradation and restore the health of his soil, see Crovetto (1996).

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with some kind of conservation tillage by about 2020. Already, 80% or more of the cropland in a few areas within the United States is managed with conservation tillage, and these areas occur in both hot and cold, and both wet and dry regions of the nation (Table 17.10).

No-tillage systems, especially, have spread to nearly all regions of the USA and are now used in some form on almost half of all the conservation tillage hectares. The no-till system has been used continuously on some farms in the eastern United States since the 1970s (nearly half a century without any tillage). No-tillage and other conservation sys*tems are now used in all parts of the world*, but the earliest and most widespread adoption has been mainly in the Americas and Australia (Figure 17.24). One of the most significant examples of no-tillage expansion has been in southern Brazil. In addition to large farms similar to those in North America, thousands of small-scale soybean and corn farmers in Brazil have successfully adapted cover-crop-based no-tillage systems using hand-pushed, animal drawn, or small tractor pulled equipment.

Table 17.9
THE EFFECT OF TILLAGE SYSTEMS IN NEBRASKA ON THE PERCENTAGE OF LAND SURFACE COVERED BY CROP RESIDUES
Note that the conventional moldboard plow system provided essentially no cover, while no-till and planting on a ridge (ridge till) provided best cover.

		Percentage of fields with residue cover greater than			
Tillage system	**Number of fields**	**15%**	**20%**	**25%**	**30%**
Moldboard	33	3	0	0	0
Chisel	20	40	15	5	0
Disk	165	40	20	9	4
Field cultivator	13	46	23	0	0
Ridge till (till, plant)	2	100	50	50	0
Shallow vertical/turbo till	14	100	100	100	100
No-till	3	100	100	100	100

Data selected from Dickey et al. (1987), except vertical/turbo tillage data from Klingberg and Weisenbeck (2011).

Table 17.10
ADOPTION OF NO-TILL AND COVER CROPPING PRACTICES IN DIVERSE PARTS OF THE USA
The use of these two conservation agriculture practices varied widely from state to state but did not appear to be related to each other or to climatic and agricultural conditions. The adoption of no-till is expected to steadily grow while the use of cover crops appears to be rapidly accelerating.

U.S. state	Agricultural conditions	Total cropland, ha	Area no-tilled, %	Area cover-cropped, %
California	Dry, hot, irrigated horticulture	3,915,013	2.1	3.6
Kentucky	Humid, moderate, mixed crops	2,586,223	36.4	5.6
Maryland	Humid, moderate, corn/soy/wheat	569,855	54.9	23.5[a]
Texas	Dry, hot, dryland crops	11,896,954	8.8	3.1
North Carolina	Humid, hot, corn, soy, cotton	1,921,731	39.5	8.3
Montana	Dry, cold, dryland crops	6,893,982	40.2	0.8
Wisconsin	Humid, cold, dairy, corn/soy	4,045,302	17.8	5.6
Entire USA	—	159,057,312	24.7	2.6

[a]The State of Maryland heavily subsidized the use of cover crops to reduce nitrogen loading to the Chesapeake Bay.
Data selected from USDA National Agricultural Statistics Service (2014).

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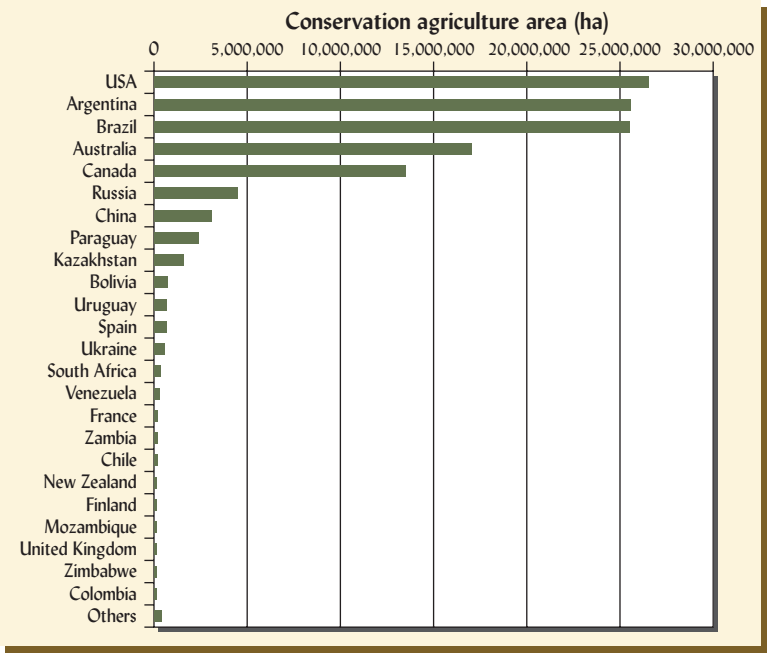

Figure 17.24 *Adoption of conservation agriculture (mainly high residue tillage or no-till) on farms in most of the world has lagged far behind that in Australia and North and South America.* [Data selected from Friedrich et al. (2012)]

Vertical or Turbo Tillage. A decade into the twenty-first century, some long-term no-till farmers began to perceive thick surface accumulations of crop residues to be an obstacle to incorporation of livestock manures and lime and to soil warming and seed placement in spring. These and other farmers have favored using new types of high speed tillage implements designed to chop up residues and so stir, but not invert, portions of the soil to shallow depths. These new generation of machines feature several sets or gangs of either smooth or fluted rolling knives (coulters) that disturb the soil mainly in a vertical (rather than horizontal) direction by producing, hence the process is sometimes referred to as vertical tillage. These implements generally include two gangs of rolling coulter blades, spaced about 20–30 cm apart, with the coulters on the rear gang off-set from those on the front gang (Figure 17.25). The operation forms stirred slots in the soil about 4–6 cm wide and 4–8 cm deep spaced every 10–15 cm across the width of the implement, thus disturbing about 30–40% of the soil surface. Turbo tilling may maintain some 30–80% residue coverage to protect from water erosion, but also creates a high potential for tillage erosion (see Section 17.13) because the high speed of the operation results in much soil being thrown.

Erosion Control by Conservation Tillage

Since conservation tillage systems were initiated, hundreds of field trials have demonstrated that these tillage systems allow much less soil erosion than do conventional tillage methods. Surface runoff is also decreased, although the differences are not as pronounced as with soil erosion (Figure 17.26). These differences are reflected in the much lower *C* factor values assigned to conservation tillage systems (see Table 17.6).

The erosion-control value of an undisturbed surface residue mulch was discussed in the previous section. The development of biopores in no-till soils promotes much more rapid infiltration and therefore much less runoff loss than is the case with conventionally tilled oils.

Figure 17.25 *Fast, shallow tillage operations that disturb only narrow strips of soil to less than 8 cm deep are commonly termed turbo till or vertical tillage. Turbo till implements employ gangs of rolling knives to chop up crop residues and partially incorporate them into slits made in the soil about 4–6 cm wide and 4–8 cm deep. Some 30–80% residue coverage may be maintained to give protection from water erosion, but the potential for tillage erosion (see Section 17.13) is quite high because the high speed of the operation results in much soil being thrown.* (Photo courtesy of John Nowatzki, North Dakota State University)

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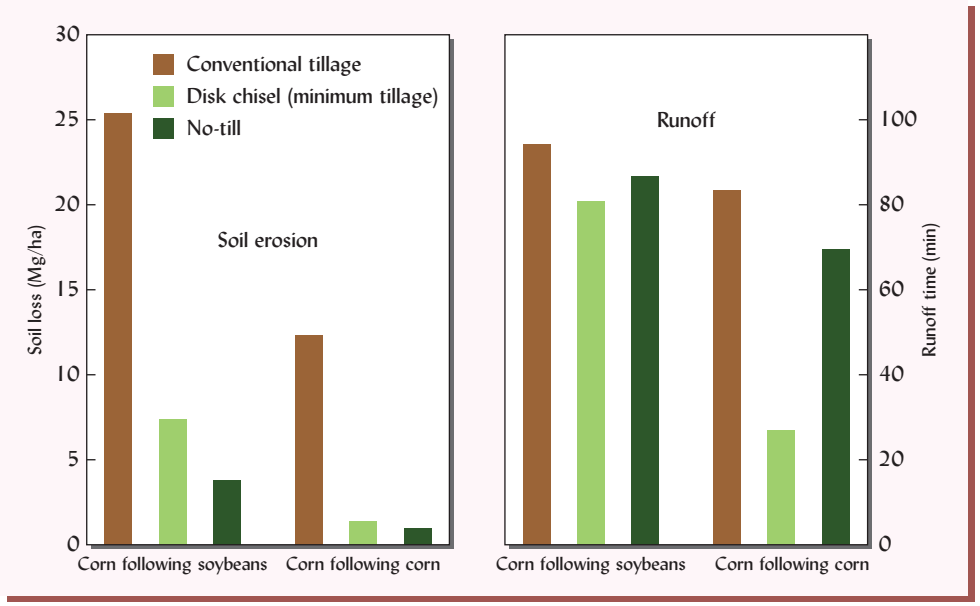

Figure 17.26 *Short-term effect of tillage systems on soil erosion and runoff from corn plots in Illinois following corn and following soybeans. Soil loss by erosion was dramatically reduced by the conservation tillage practices. The period of runoff was reduced most in this short-term study by the disk chisel system where corn was grown after corn. The soil was a Typic Argiudoll (Catlin silt loam), 5% slope, planted up- and downslope, tested in early spring.* [Data from Oschwald and Siemens (1976)]

Conservation tillage also significantly reduces the loss of nutrients dissolved in runoff water or attached to sediment (review Tables 14.3 and 16.2).

Effect on Soil Properties

When soil management is converted from plow tillage to conservation tillage (especially no-tillage), numerous soil properties are affected, mostly in favorable ways. The changes are most pronounced in the upper few centimeters of soil (Figure 12.32). Generally, the changes are greatest for systems that produce the most plant residue (such as corn and small grains in humid regions, especially if accompanied by cover crops), retain the most residue coverage, and cause the least soil disturbance. Many of these changes are illustrated in other chapters of this textbook, so the discussion here will be brief.

Physical Properties. Macroporosity and aggregation (see Sections 4.5 and 4.8) are increased as active organic matter builds up and earthworms and other organisms establish themselves. Infiltration and internal drainage are generally improved, as is soil water-holding capacity. Some of these effects are illustrated in Figure 17.27. The enhanced infiltration capacity of no-till-managed soils is generally quite desirable, but in some cases it may lead to more rapid leaching of nitrates and other water-soluble chemicals. Residue-covered soils are generally cooler and more moist (see Sections 6.4 and 7.11). This is an advantage in the hot part of the year, but may be detrimental to early crop growth in the cool spring of temperate regions.

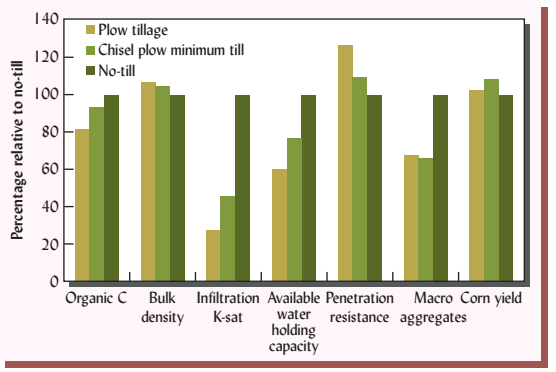

Figure 17.27 *The comparative effects of 49 years of three tillage systems on soil organic matter content (0–30 cm), soil physical soil properties (0–10 or 0–20 cm), and corn yields averaged across two fine-textured soils in Ohio, USA (a Fragiudalf and an Epiaqualf), growing continuous corn and corn–soybean rotations without cover crops. Values for the no-till system were taken as 100, and the others are shown in comparison. Bulk density (0–10 cm) and corn yields (five-year average) were about the same for each tillage system, but for all other properties the no-till system was decidedly more beneficial than either of the other two systems. No-till management had especially large impacts on saturated hydraulic conductivity (0–10 cm), available water holding capacity (0–20 cm), and macroaggregation (>2 mm).* [Graphed from data in Kumar et al. (2012a) and Kumar et al. (2012b)]

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In cool regions, soils with restricted drainage may yield somewhat less using conservation tillage, because soil conditions are wetter and cooler than with conventional tillage. Reduced yields have discouraged the adoption of conservation tillage in these regions. However, limited preplanting tillage just over the crop row (known as strip tillage, see Section 7.11) or ridge tillage are conservation tillage systems that allow at least part of the soil to warm faster and largely overcome these problems.

Chemical Properties. No-tillage systems significantly increase the organic matter content of the upper few centimeters of soil (see Figures 17.27 and 12.32). During the initial four to six years of no-till management, the buildup of organic matter results in the immobilization of nutrients (see Section 12.3), especially nitrogen. This is in contrast to the mineralization of nutrients that is encouraged by the decline of soil organic matter under conventional tillage. Eventually, when soil organic matter stabilizes at a new higher level, nutrient mineralization rates under no-till increase. Higher moisture and lower oxygen levels may also stimulate denitrification (see Section 13.8). These processes sometimes result in the need for greater levels of nitrogen fertilization for optimum yields during the early years of no-till management.

In no-tillage systems, nutrient elements tend to accumulate in the upper few centimeters of soil as they are added to the surface in crop residues, animal manures, chemical fertilizers, and lime. However, research indicates that because of the surface mulch, crop roots (like those of trees in the untilled forest soil environment) have no trouble obtaining nutrients from the near-surface soil layers. The stratification must be taken into account in sampling soils for fertility testing (see Section 16.11), and may increase the concentration of nutrients dissolved in surface runoff water.

Without tillage to mix the soil, the acidifying effects of nitrogen oxidation, residue decomposition, and rainfall are concentrated in the upper few centimeters of soil, the pH of which may drop more rapidly than that of the whole plow layer in conventional systems (see Section 9.5). This acidity can be countered by application of liming materials to the soil surface.

Biological Effects. The abundance, activity, and diversity of soil organisms tend to be greatest in conservation tillage systems characterized by high levels of surface residue, year round diverse vegetation, and little physical soil disturbance (see Section 11.14). Earthworms and fungi, both important for soil structure, are especially favored (see Table 11.10). However, organic residues left on the surface in no-till are actually more slowly decomposed than those incorporated by conventional tillage. No-till residues are in less intimate contact with the soil particles so their breakdown is delayed, increasing the length of time they remain as a protective surface barrier.

17.7 VEGETATIVE BARRIERS

Narrow rows of permanent vegetation (usually grasses or shrubs) planted on the contour can be used to slow down runoff, trap sediment, and eventually build up "natural" or "living" terraces (Figure 17.28). In some situations, tropical grasses (e.g., a deep-rooted, drought-tolerant species like *vetiver grass or elephant grass*) have shown considerable promise as an affordable alternative to the construction of terraces.

The deep-rooted grass plants have dense, stiff stems that tend to filter out soil particles from muddy runoff and catch soil thrown downslope by tillage. This sediment and soil accumulates on the upslope side of the grass barrier and, in time, actually creates a terrace that may be more than 1 m above the soil surface on the downslope side of the plants. Vetiver grass is particularly well suited to survive under harsh conditions, as its root system can forage deeply for water and its foliage is not palatable to wandering cattle. Other grasses are used that can serve a dual purpose as cattle fodder, but these tend to take more water out of the root zone of the adjacent food crops.

Similar narrow grass hedges have effectively reduced runoff and erosion from soils in Midwestern United States (Figure 17.29). Also, research is being conducted to evaluate numerous systems of vegetative barriers that combine grasses with trees especially in some tropical countries. Such systems may provide many benefits (fruit, firewood, fodder, and nutrient-rich mulch) in addition to erosion control, making them more attractive to farmers

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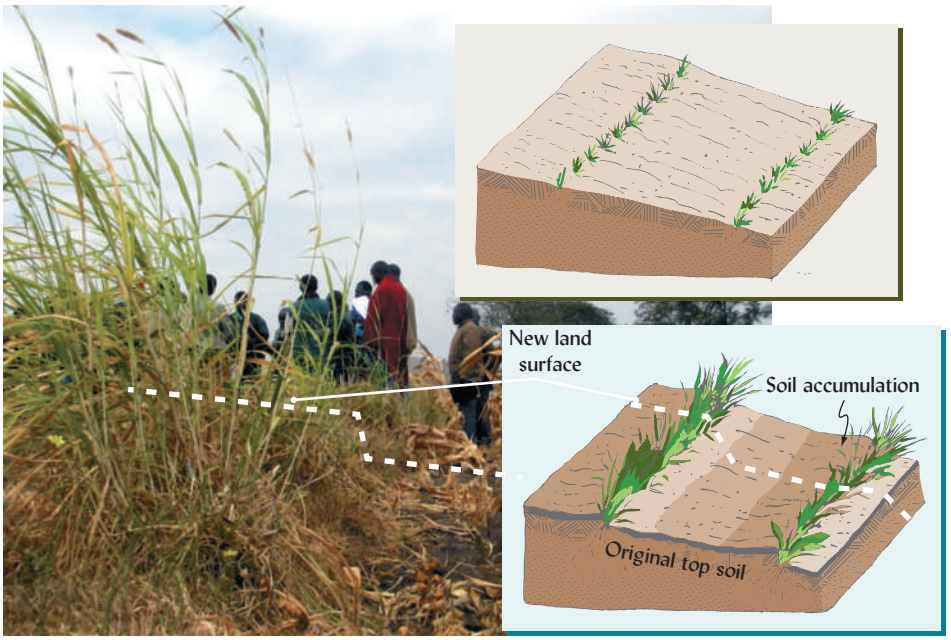

Figure 17.28 *Vegetative barriers create natural terraces. (Photo) Elephant grass has been vegetatively planted on the contour in a crop field. (a) Root cuttings are planted perpendicular to the slope direction. In a year or so the dense grass root and shoot growth will serve as a barrier to hold soil particles while permitting some water to pass on through. (b) Soil eventually accumulates above the grass, basically forming a terrace wall, as indicated by the different levels on which the people are standing.* (Photo and diagram courtesy of Ray R. Weil)

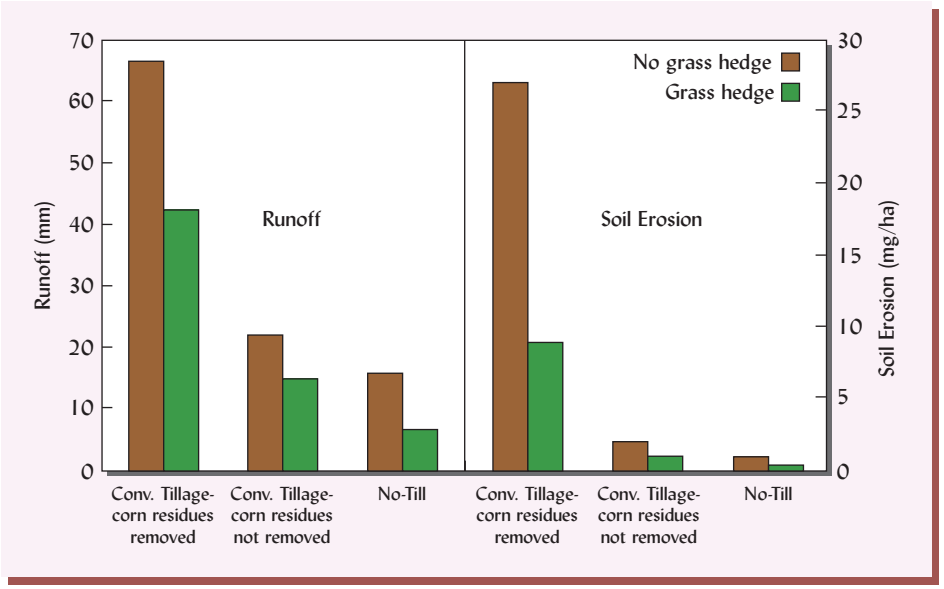

Figure 17.29 *Narrow grass hedges can be effective tools to reduce losses of runoff water and soil. Switchgrass hedges 0.72 m wide were established across the slope every 16 m in a field of continuous corn that then received a total of 120 mm of simulated rainfall. The soil was a Typic Hapludoll in Iowa with an average slope of 12%. Corn residues left on the soil surface as well as no-till systems also drastically reduced losses, especially of the soil.* [Data estimated from a figure in Gilley et al. (2000)]

who must invest their limited labor and resources in establishing such conservation practices. In temperate regions, conservation technologies (like the buffer strips and winter cover crops discussed in Sections 16.2) will improve crop production in the short term as well as protect soil and water quality in the longer term. The benefits of reduced erosion and increased crop yields resulting from several vegetation-based erosion-control practices are summarized in Table 17.11.

17.8 CONTROL OF GULLY EROSION AND MASS WASTING

Gullies rarely form in soils protected by healthy, dense, forest, or sod vegetation, but are common on deserts, sparsely vegetated rangeland, and open woodland in which the soil is only partially covered. Gullies also readily form in soils exposed by tillage or grading if small rills

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Table 17.11
RANGE IN THE EFFECTS OF MULCHING, CONTOUR CULTIVATION, AND GRASS CONTOUR HEDGES ON SOIL EROSION AND CROP YIELDS

Practice	Reduction in soil erosion, %	Increase in crop yield, %
Mulching	78–98	7–188
Contour cultivation	50–86	6–66
Grass contour hedges	40–70	38–73

From Doolette and Smyle (1990), a review of more than 200 studies.

Figure 17.30 *The devastation of gully erosion.* (Left) *Gully erosion in action on a highly erodible soil in western Tennessee, USA. The roots of the small corn plants are powerless to prevent the cutting action of the concentrated water flow.* (Right) *The legacy of neglect of human-induced accelerated erosion. Tillage of sloping soils during the days of the Roman Empire began a process of accelerated erosion that eventually turned swales into jagged gullies that continue to cut into this Italian landscape with each heavy rain. For a sense of scale, note the dark olive trees and white houses on the grassy, gentle slopes of the relatively uneroded hilltops.* (Left photo courtesy of the USDA Natural Resources Conservation Service; right photo courtesy of Ray R. Weil)

are allowed to coalesce so that running water eats into the land (Figure 17.30, *left*). Water concentrated by poorly designed roads and trails may cause gullies to form even in dense forests. In many cases, neglected gullies will continue to grow and after a few years, devastate the landscape (see Figure 17.30, *right*). On the other hand, in some stony soils a layer of rock fragments left behind when finer particles are scoured away may protect the gully channel bottom from further cutting action.

Remedial Treatment of Gullies

If small enough, gullies can be filled in, shaped for smooth water flow, sown to grass, and thereafter be left undisturbed to serve as grassed waterways. When the gully erosion is too active to be checked in this manner, more extensive treatment may be required. If the gully is not too large, a series of check dams about 0.5–1 m high may be constructed at intervals of 4–9 m, depending on the slope. These small dams may be constructed from materials available on site, such as large rocks, rotted hay bales, brush, or logs. Wire netting may be used to stabilize such structures made from stones. Check dams, whether large or small, should be constructed with the general features illustrated in Figure 17.31. After a time, enough sediment may collect behind the dams to form a series of bench terraces which may be cultivated or put into permanent sod. Improperly constructed check dams, however, may make matters worse when water washes around them, enlarging the gully (Figure 17.31, *left*).

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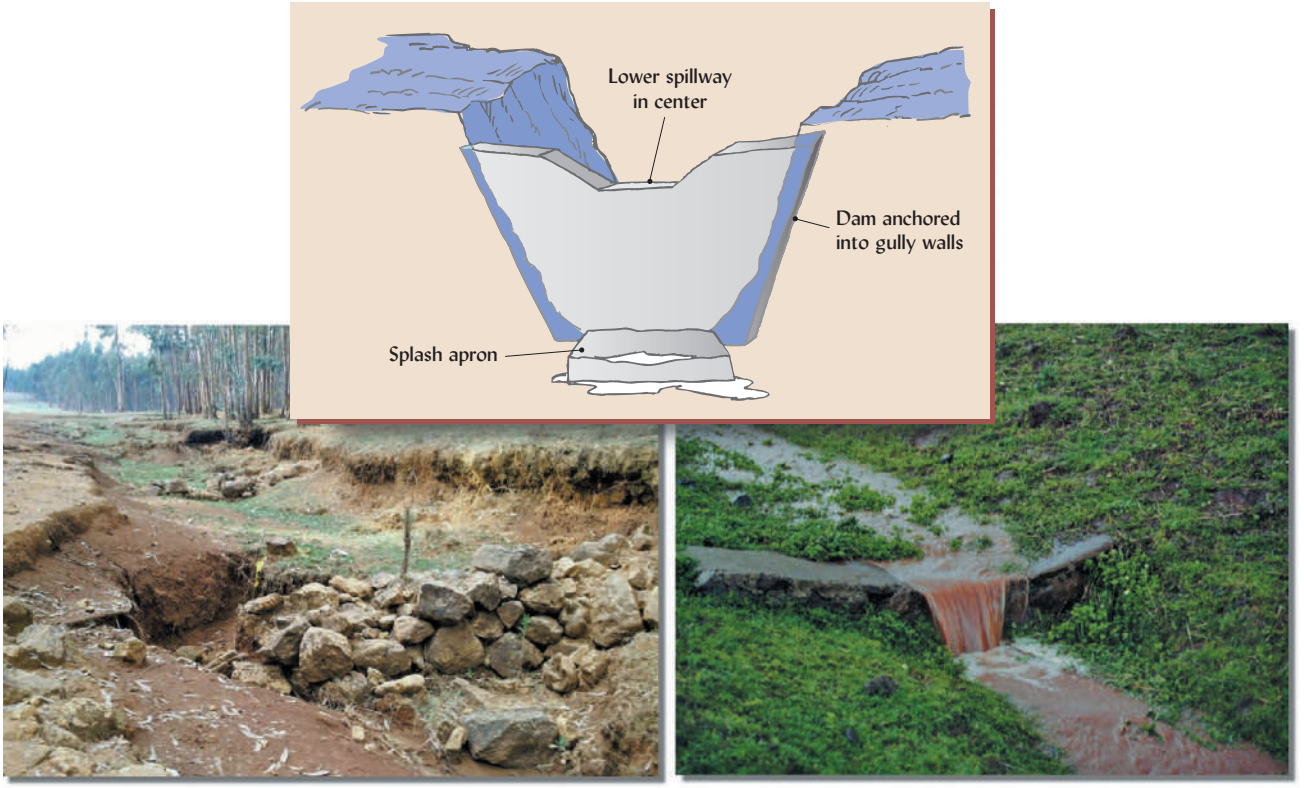

Figure 17.31 *A schematic drawing of a check dam used to arrest gully erosion* (upper center). *Whether made from rock, brush, concrete, or other materials, a check dam should have the general features shown. The structure should be dug into the walls of the gully to prevent water from going around it. The center of the dam should be lower so that water will spill over there and not wash out the soil of the gully walls. An erosion-resistant apron made from densely bundled brush, concrete, large rocks, or similar material should be installed beneath the center of the dam to prevent the overflow from undercutting the structure. An effective check employing these features is shown at the right. In contrast to the gully-healing effect of a well-designed check dam, the haphazard dumping of rocks, brush, or junked cars into a gully will make matters worse, not better* (left). (Diagram and photos courtesy of Ray R. Weil)

With very large gullies, it may be necessary to divert the runoff away from the head of the channel and install more permanent dams of earth, concrete, or stone in the channel itself. Again, sediment deposited above the dams will slowly fill in the gully. Semipermanent check dams, flumes, and channels lined with large rock are also used on construction sites, but are generally too expensive for extensive use on agricultural land.

Mass Wasting on Unstable Slopes

The downhill movement of large masses of unstable soil (**mass wasting**, see also Section 4.9) is quite different from the erosion of the soil surface, which is the main topic of this chapter. Mass wasting most commonly occurs on very steep slopes (usually greater than 60% slope). While this type of soil loss sometimes occurs on steep pastures, it is most common on non-agricultural land. Mass wasting can take several forms. **Soil creep** is the slow deformation (without shear failure) of the soil profile as the upper layers move imperceptibly downhill. As the soil of a forested slope deforms, trees attempting to right themselves produce curved trunks, a common sign of soil creep (see Figure 4.58). **Mud flows** involve the partial liquefaction and moderately rapid flow of saturated soil due to loss of cohesion between particles (see Figure 4.58). **Landslides** occur when sudden shear failure, usually under very wet conditions, causes the rapid downhill movement of a mass of soil (Figure 17.32).

Mass wasting is sometimes triggered by human activities that undermine natural stabilizing forces or cause the soil to become water saturated as a result of concentrated water flow. The rotting of large soil-anchoring tree roots several years after clear-cutting a forest or excavations cutting into the toe of a steep slope are all-too-common examples.

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Figure 17.32 *While erosion by water and wind removes material from just the soil surface, mass wasting moves a much thicker layer of soil and regolith materials all at once. Mass wasting includes both gradual processes such as soil creep and moderately rapid processes such as mud flows, as well as sudden processes such as the landslide that occurred in the scene shown here (for scale, note the man standing on a sheared and partially rotated soil block).* (Photo courtesy of Ray R. Weil)

17.9 CONTROL OF ACCELERATED EROSION ON RANGE- AND FORESTLAND

Rangeland Problems

Many semiarid rangelands lose large amounts of soil under natural conditions (see Figure 17.4), but accelerated erosion can lead to even greater losses if human influences are not managed carefully. Overgrazing by cattle, which leads to the deterioration of the vegetative cover on rangelands, is a prime example (Figure 17.33). Grass cover generally protects the soil better than the scattered shrubs that usually replace it under the influence of poorly managed livestock grazing. In addition, cattle congregating around poorly distributed water sources and salt licks may completely denude the soil. Cattle trails, as well as ruts from off-road vehicles, can channelize runoff water and spawn gullies that eat into the landscape. Because of the prevalence of dry conditions, wind erosion (to be discussed in Sections 17.11 and 17.12), also plays a major role in the deterioration of rangeland soils. It, too, is accelerated by when soils are left bare of vegetation because of overgrazing or tillage for crop production.

Erosion on Forestlands

In contrast to deserts and rangelands, land under healthy, undisturbed forests loses very small amounts of soil. However, accelerated erosion can be a serious problem on forested land, both because the rates of soil loss may be quite high and because the amount of land involved may be enormous. The main cause of accelerated erosion in forested watersheds is usually the construction of logging roads, timber-harvest operations, and the trampling of trails and off-trail areas by large numbers of recreational users (or cattle, in some areas).

To understand and correct these problems, it is necessary to realize that the secret of low natural erosion from forested land is the undisturbed forest floor; the O horizons protect the soil from the impact of raindrops and allow such high infiltration rates that surface runoff is very small or absent. Contrary to the common perception, it is the forest floor, rather than the tree canopy or roots, that protects the soil from erosion (Figure 17.34, *left*). In fact, rainwater dripping from the leaves of tall trees forms very large drops that reach terminal velocity and impact the ground with more energy than direct rain from even intense storms. If the forest floor has been disturbed and mineral soil exposed, serious splash erosion can result (see Figure 17.34, *right*). Gully erosion can also occur under the forest canopy if water is concentrated, as by unplanned footpaths or poorly designed roads.

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Figure 17.33 *Overstocking and poorly managed grazing is a major cause of soil erosion and degradation worldwide.* (Left) *Damaged vegetative cover and eroded soil caused by too many poorly managed cattle in a semiarid rangeland in East Africa.* (Right) *Soil and water quality in a humid region of eastern North America damaged by overstocking with cattle (note the differences in soil erosion, vegetation, and stream configuration between the left and right side of the fence).* (Photos courtesy of Ray R. Weil)

Figure 17.34 *The leaf mulch on the forest floor, rather than the tree roots or canopy, provides most of the protection against erosion in a wooded ecosystem.* (Left) *An undisturbed temperate deciduous forest floor (as seen through a rotten stump). The leafless canopy will do little to intercept rain during winter months. During the summer, rainwater dripping from the foliage of tall trees may impact the forest floor with as much energy as unimpeded rain.* (Right) *Severe erosion has taken place under the tree canopy in a wooded area where the protective forest floor has been destroyed by foot traffic. The exposed tree roots indicate that nearly 25 cm of the soil profile has washed away.* (Photos courtesy of Ray R. Weil)

Practices to Reduce Soil Loss Caused by Timber Production[13]

The main sources of eroded soil from timber production are *logging roads* (that are built to provide access to the area by trucks), *skid trails* (the paths along which logs are dragged), and *yarding areas* (the places where collected logs are sized and loaded onto trucks). Relatively

[13]For general introduction to this topic, see Nyland (1996). For an analysis of erosion causes on steep forest lands in the tropics, see Sidle et al. (2006).

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little erosion results directly from the mere felling of the trees (except where large tree roots are needed to anchor the soil against mass wasting, as discussed in Section 17.8). Strategies to control erosion should include consideration of: (1) intensity of timber harvest, (2) methods used to remove logs, (3) scheduling of timber harvests, and (4) design and management of roads and trails. Soil disturbance in preparation for tree regeneration (such as tillage to eliminate weed competition or provide better seed-to-soil contact) must also be limited to sites with low susceptibility to erosion.

Intensity of Timber Harvest. On the steepest, most erodible sites, environmental stewardship may require that timber harvest be foregone and the land be given only protective management. On somewhat less susceptible sites, selective cutting (occasional removal of only the oldest trees) may be practiced without detrimental results. The shelterwood system (in which a substantial number of large trees are left standing after all others are harvested) is probably the next most intensive method and can be used on moderately susceptible sites. Clear-cutting (removal of all trees from large blocks of forest) should be used only on gentle slopes with stable soils.

Method of Tree Removal. The least expensive and most commonly used method of tree removal is by wheeled tractors called *skidders* (see Figure 4.47). This method generally disrupts the forest floor, exposing the mineral soil on perhaps 30–50% of the harvested area. In contrast, more expensive methods using cables to lift one end of the log off the ground are likely to expose mineral soil on only 15–25% of the area. For very sensitive sites, logs can be lifted to yarding areas by balloon or helicopter, practices which are very expensive but result in as little as 4–8% bare mineral soil.

Scheduling of Timber Harvest. Much erosion can be prevented by limiting entry into the forest by machinery to those periods when the soil is either dry or (in temperate regions) frozen and covered with snow. Damage to the forest floor (including both compaction and exposure of mineral soil) occurs much more readily if the soil is very wet. In addition, wheel ruts easily form in wet soils and channel runoff to initiate gully erosion.

Design and Management of Roads. Poorly built logging roads may lose as much as 100 Mg/ha of soil by erosion of the road surface, the drainage ditch walls, or the soil exposed by road cuts into the hillside. Roads also collect and channelize large volumes of water, which can cause severe gullying. Roads should be so aligned as to avoid these problems. Although expensive, placing gravel on the road surface, lining the ditches with rocks, and planting perennial vegetation on exposed road cuts can eliminate up to 99% of the soil loss. A much less expensive measure is to provide cross channels (shallow ditches or **water bars**, as shown in Figure 17.35, *right*) every 25–100 m to prevent excessive accumulation of water and safely spread it out onto areas protected by natural vegetation. After timber harvest is complete, the roads in an area should be grassed over and closed to traffic.

Design of Skidding Trails. Skidding trails that lead runoff water downhill toward a yarding area invite the formation of gullies. Repeated trips dragging logs over the same secondary trails also greatly increase the amount of mineral soil exposed to erosive forces. Both practices should be avoided, and yarding areas should be located on the highest-elevation, most level, and well-drained areas available (Figure 17.35, *left*).

Buffer Strips Along Stream Channels. When forests are harvested, buffer strips as wide as 1.5 times the height of the tallest trees should generally be left untouched along all streams (Figure 17.35, *left*). As discussed in Section 16.2, buffer strips of dense vegetation have a high capacity to remove sediment and nutrients from runoff water. Forested buffers also protect the stream from excessive logging debris. In addition, streamside trees shade the water, protecting it from the undesirable heating that would result from exposure to direct sunlight.

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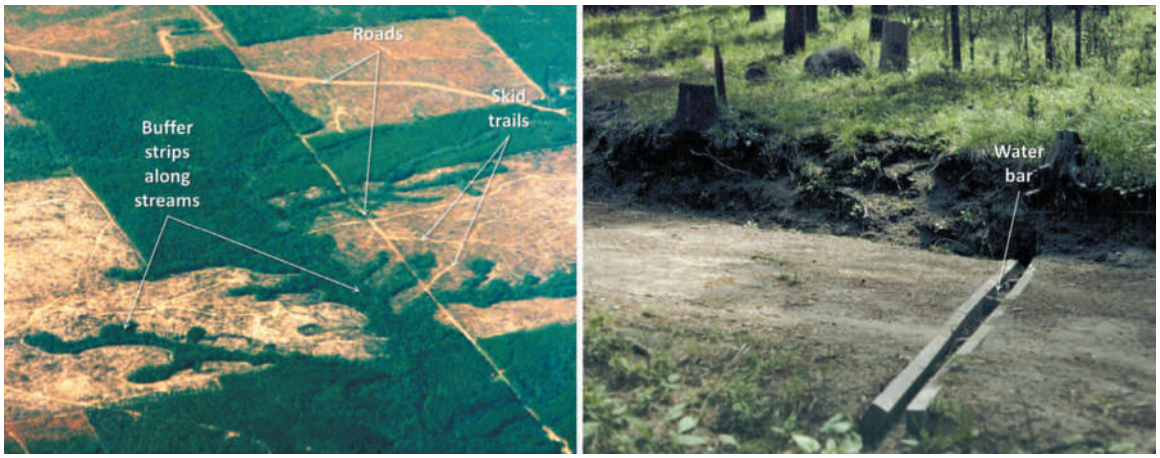

Figure 17.35 *Two important forestry practices designed to minimize damage from erosion due to timber harvests. (*Left*) An aerial view of clear-cut and unharvested block of pine forest in Alabama, USA. Narrow skid trails can be seen leading up to a staging area located on high ground and spreading apart going downhill toward the streams. This is in contrast to the common and easier practice of dragging logs downhill so that skid trails converge at a low point, inviting runoff water to concentrate into gully-cutting torrents. Also visible are several dark-colored buffer strips where the trees were left undisturbed along streams to provide protection for water quality. (*Right*) An open-top culvert (also called a water bar) in a well-designed logging road in Montana, USA. This simple structure, along with proper road bed alignment, can greatly reduce gully erosion caused by water flowing unimpeded along roads and trails in forested areas. Water bars placed at frequent intervals lead runoff water, a little at a time, off the road and into densely vegetated areas.* (Photos courtesy of Ray R. Weil)

17.10 EROSION AND SEDIMENT CONTROL ON CONSTRUCTION SITES

Although active construction sites cover relatively little land in most watersheds, they may still be a major source of eroded sediment because the potential erosion per hectare on drastically disturbed land is commonly 100 times that on agricultural land. Heavy sediment loads are characteristic of rivers draining watersheds in which land use is changing from farm and forest to built-up land. Historically, once urbanization of a watershed is complete (all land being either paved over or covered by well-tended lawns), sedimentation rates return to levels as low (or lower) than before the development took place.

To prevent serious sediment pollution from construction sites, governments in the United States (e.g., through state laws and the Federal Clean Water Act of 1992) and in many other industrialized countries require that contractors develop detailed erosion- or sediment-control plans before initiating construction projects that will disturb a significant area of land. The goals of erosion control on construction sites are: (1) to avoid on-site damage, such as undercutting of foundations or finished grades and loss of topsoil needed for eventual landscaping and (2) to retain eroded sediment on-site so as to avoid all the environmental damages (and liabilities) that would result from deposition of sediment on neighboring land and roads, and in ditches, storm water drains, reservoirs, and streams.

Principles of Erosion Control on Construction Sites

Five basic steps are useful in developing plans to meet the aforementioned goals:

1. When possible, schedule the main excavation activities for low-rainfall periods of the year.
2. Divide the project into as many phases as possible, so that only a few small areas must be cleared of vegetation and graded at any one time.
3. Cover disturbed soils as completely as possible, using vegetation or other materials.
4. Control the flow of runoff to retain or detain most of the water and move the excess safely off the site without destructive gully formation.
5. Trap the sediment before releasing the excess runoff water off-site.

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The last three steps bear further elaboration. They are best implemented as specific practices integrated into an overall erosion-control plan for the site.

Keeping the Disturbed Soil Covered

Soils freshly disturbed by excavation or grading operations are characterized by very high erodibility (*K* values). This is especially true for low-organic-matter subsoil materials. Potential erosion can be extremely high (200–400 Mg/ha is not uncommon) unless the *C* value is made very low by providing good soil cover. This is best accomplished by allowing the natural vegetation to remain undisturbed for as long as possible, rather than clearing and grading the entire project area at the beginning of construction (see step 1, preceding). Once a section of the site is graded, any sloping areas not directly involved in the construction should be sodded or sown to fast-growing grass species adapted to the soil and climatic conditions.

Seeded areas should be covered with **mulch** or specially manufactured **erosion mat or blankets** (Figure 17.36, *right*). Erosion blankets, made of various biodegradable or nonbiodegradable materials, provide instant soil cover, protect the seed from being washed away, and are highly effective at reducing soil erosion (Figure 17.37).

A commonly used technology to protect steep slopes and areas difficult to access, such as road cuts, is the **hydroseeder** (Figure 17.36, *left*) that sprays out a mixture of seed, fertilizer, lime (if needed), mulching material, and sticky polymers. Good construction-site management includes removal and stockpiling of the A-horizon material before an area is graded (see Figure 1.16). This soil material is often quite high in fertility and is a potential source of sediment and nutrient pollution. The stockpile should therefore be given a grass and mulch cover to protect it from erosion until it is used to provide topsoil for landscaping around the finished structures.

Controlling the Runoff

Freshly exposed and disturbed subsoil material is highly susceptible to the cutting action of flowing water. The gullies so formed may ruin a grading job, undercut pavements and foundations, and produce enormous sediment loads. The flow of runoff water must be controlled by carefully planned grading, terracing, and channel construction. Most construction sites require a perimeter waterway to catch runoff before it leaves the site and to channel it to a retention basin.

The sides and bottom of such channels must be covered with "armor" to withstand the cutting force of flowing water. Where high water velocities are expected, the soil must

Figure 17.36 *Two means of providing rapid temporary soil cover while establishing vegetation on erodible slopes.* (Left) *A* **hydroseeder** *spraying a mixture of water, chopped straw, grass seed, fertilizer, and sticky polymers (inset close-up) that holds the mulch in place until the grass seed can take root. Hydroseeding is especially useful for efficiently establishing vegetative cover on difficult-to-reach areas.* (Right) **Erosion-control mats** *or blankets made of plastic netting or natural materials like wood fiber or jute (shown here) are rolled out over newly seeded grass to hold the seed and soil in place until the vegetative cover is established. In the inset, young grass seedlings are exposed as the jute erosion blanket is pulled away.* (Photos courtesy of Ray R. Weil)

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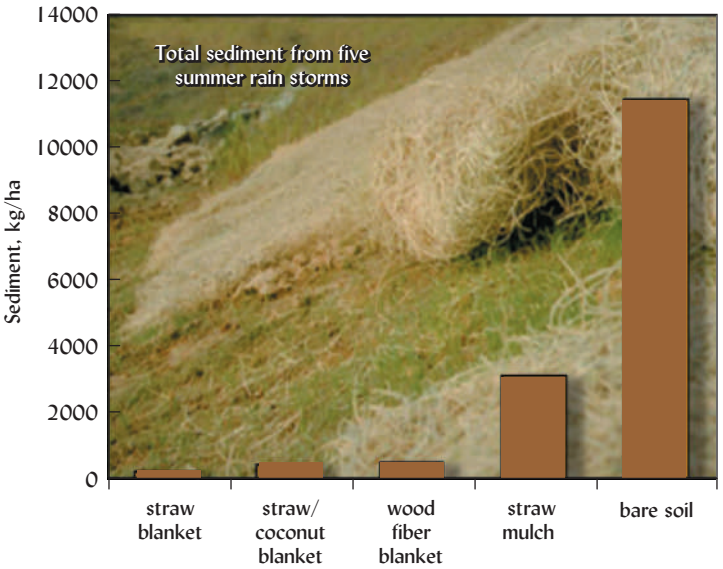

Figure 17.37 *Total sediment generated by five summer storms on construction site soil left bare or protected by straw mulch or various types of commercial erosion blankets. The clayey soil met the government's specifications for topsoil. It was raked, fertilized, and seeded to grass mixture. The experimental plots had a 35% slope gradient and were 9.75 m long. Immediately after seeding, the soils were covered by the various erosion-control materials. The best grass vegetative cover and biomass was achieved on straw mulch plots in the first year. The best short-term sediment control was achieved by the commercial blankets, such as the wood-fiber blanket shown in the background photo.* [Drawn from data in Benik et al. (2003); photo courtesy of Ray R. Weil]

be protected with **hard armor** such as **riprap** (large angular rocks, such as are shown in Figure 17.38), **gabions** (rectangular wire-mesh containers filled with hand-sized stone), or interlocking concrete blocks. Before installing the hard armor, the soil is first covered with a **geotextile** filter cloth (a tough nonwoven material) to prevent mixing of the soil into the rock or stone.

In smaller channels, and on more gentle slopes where relatively low water velocities will be encountered, **soft armor**, such as grass sod or erosion blankets, can be used. Generally, soft armor is cheaper and more aesthetically appealing than hard armor, and can lead to a more naturally functioning waterway once the plant community becomes fully established. Newer approaches to erosion control often involve physically reinforced vegetation such as trees or grasses planted in openings between concrete blocks or in tough erosion mats.

The term **bioengineering** describes techniques that use vegetation (locally native, non-invasive species are preferred) and natural biodegradable materials to protect channels subject to rather high water velocities. Examples include the use of **brush mattresses** to stabilize

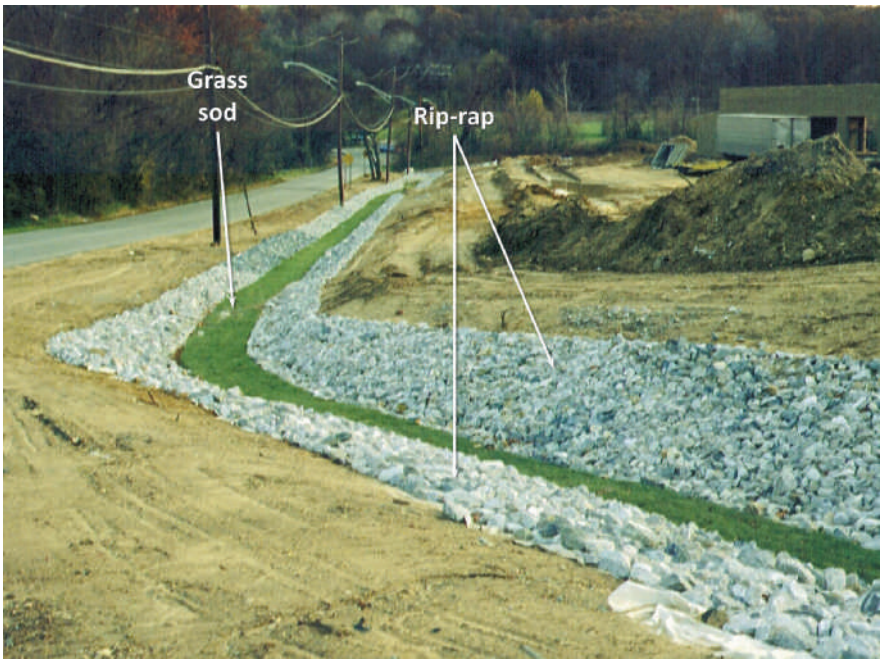

Figure 17.38 *The flow of runoff from large areas of bare soil must be carefully controlled if off-site pollution is to be avoided. Here, a carefully designed channel with a grass sod bottom and sides lined with large rocks (riprap) prevents gully erosion, reduces soil loss, and guides runoff around the perimeter of a construction site.* (Photo courtesy of Ray R. Weil)

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steep slopes. In this technique, live tree branches are tightly bundled together, staked down flat using long wooden pegs, and partially covered with soil. The so-called **live stake** technique (a version of which is exemplified by the willow cuttings in Figure 17.39, *right*) is another example of a bioengineering approach commonly used to stabilize soil along channels subject to high velocity water. In both cases, the soil is provided some immediate physical protection from scouring water, and eventually the dormant cuttings take root to provide permanent, deep-rooted vegetative protection.

Trapping the Sediment

For small areas of disturbed soils, several forms of sediment barriers can be used to filter the runoff before it is released. The most commonly used types of silt barriers are woven fabric silt fences and various bundles or bales of plant fiber such as straw. If installed properly, both can effectively slow the water flow so that most of the sediment is deposited on the uphill side of the barrier (Figure 17.40), while relatively clear water passes through.

On large construction sites, a system of protected slopes and channels leads storm runoff water to one or more retention and sedimentation ponds located at the lowest elevation of the site. As the flowing water meets the still water in the pond it drops most of its sediment load (Figure 17.41), allowing the relatively clear water to be skimmed off the top and released to the next pond or off the site. Wetlands (Section 7.7) are often constructed to help detain and purify the overflow from sedimentation ponds before the water is released into a natural stream or river.

Construction site erosion-control measures are commonly designed to retain the runoff from small storms on-site. The retention ponds must also be able to deal with runoff generated from intense rainstorms—the kind that may be expected to occur on a site only once in every 10 or even 100 years. In designing the capacity of sediment-retention ponds, the erosion models discussed in Section 17.4 are used to estimate the amount of sediment that is likely to be eroded from the site. While expensive to construct, well-designed sediment-retention ponds can be incorporated as permanent aesthetic water features that enhance the value of the final project.

Figure 17.39 *Stream bank erosion and its control with bioengineering techniques.* (Left) *Tumbling trees are a sign of a degraded stream with rapidly eroding banks that contribute large amounts of soils to the stream sediment load.* (Right) *A somewhat smaller stream that was similarly degraded, but has now been restored with several techniques that control bank erosion and improve water quality. The banks have been protected from scouring storm flows by both soft armor and hard armor. As soft armor, the stream banks have been seeded with a diversity of native grasses and forbs and the seeding protected temporarily by biodegradable erosion blankets. The live willow branches that are taking root along the base of the stream banks comprise another type of soft armor referred to as* live staking. *The large rocks (hard armor) protect the banks from scouring, cause water to form rapids that improve water oxygen content, and collect gravelly sediments that improve fish-spawning habitat.* (Photos courtesy of Ray R. Weil)

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Figure 17.40 *Several types of sediment-control measures used around the periphery of a construction site.* (Left) *A line of straw bales pegged to the ground allows water to seep through, but filters out much of the sediment and slows down the flow so that the water drops its sediment load.* (Right) *A properly installed silt fence effectively removes sediment from runoff water leaving the edge of a construction site. The silt fencing material is a woven plastic that allows water to flow through at a much reduced rate. Note the light-colored sediment on the inside and the undisturbed forest floor on the outside of the silt fence. A silt fence must be embedded in the soil and supported with stout stakes or posts. Improperly installed silt fencing is useless, as sediment-laden water may pass underneath or may even knock the fence over.* (Photos courtesy of Ray R. Weil)

Figure 17.41 *Sediment and storm water retention.* (Left) *The effect of a small sediment impoundment structure on the retention of suspended soil eroded from a construction site. Note the riprap-lined channel leading runoff water into the pond and the delta-like alluvial fan of sediment deposited as the water's velocity is reduced where it enters the pond. The standpipe in the background has holes that allow the clearest water near the top to overflow and leave the construction site.* (Right) *A larger sediment retention pond shown several years after construction activities were completed. A well-designed sediment structure will serve as a decorative landscaping asset to the property and continue to detain storm water and retain sediment. Only rarely does enough water accumulate to reach the outflow grating, and even then, most sediment is retained on the pond bottom.* (Photos courtesy of Ray R. Weil)

17.11 WIND EROSION: IMPORTANCE AND FACTORS AFFECTING IT[14]

Up to this point we have focused on soil erosion by water, but wind, too, causes much soil degradation and loss around the world. Generally wind erosion is most serious in dry regions and water erosion in wet regions. However, there are many places that suffer from both types of erosion, in many cases because both wet and dry seasons occur in the same location. Regions vulnerable to both wind and water erosion include the Sahel in Africa, the Pacific coast of South America, and the Loess Plateau in China (Figure 17.42).

[14]For a clearly written and detailed explanation of wind erosion and its control, see Zobeck and Van Pelt (2014).

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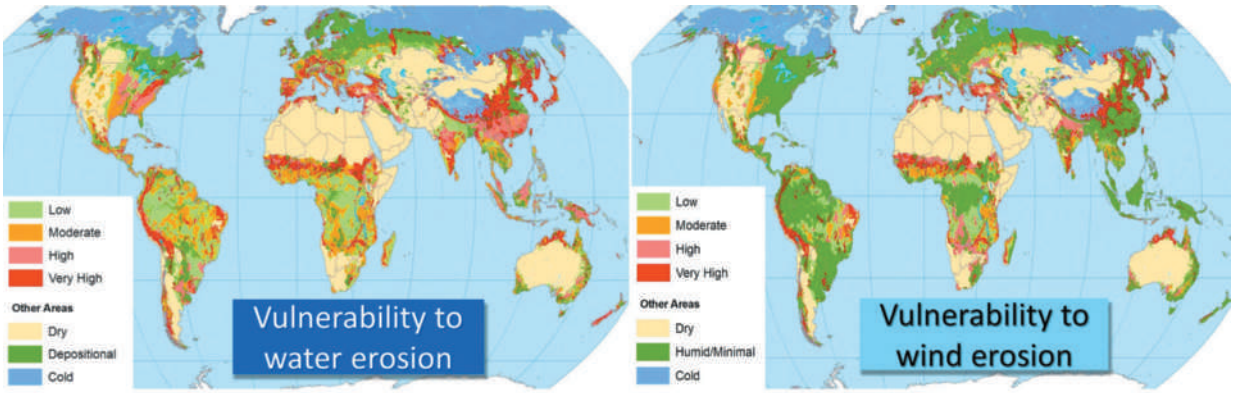

Figure 17.42 *Global distribution of soil vulnerability to erosion by water (*left*) and to erosion by wind (*right*). Climate is the main variable driving the vulnerabilities, with additional influences of topography, soil properties, and vegetation. Although generally wind erosion is most serious in dry regions and water erosion in wet regions, there are many places that suffer from both types of erosion, in many cases because both wet and dry seasons occur in the same location.* (Maps modified from USDA NRCS, Soil Survey Division, Office of World Soils)

Overgrazing of the fragile lands of arid and semiarid areas destroys the protective biological soil crusts (see Section 11.14) and much of the native vegetation. Tillage for dryland crop production also dries out and lays bare millions of hectares, making them much more vulnerable to the wind than when the native vegetation was undisturbed. Both types of mismanagement have stimulated wind erosion to depress soil productivity and bring starvation and misery to millions of people in these areas. In the United States wind moves about two-thirds as much soil as is transported by water erosion. In six of the Great Plains states, annual wind erosion exceeds water erosion on cropland, averaging from 4 Mg/ha in Nebraska to 29 Mg/ha in New Mexico, where mismanagement of plowed lands and overgrazing of range grasses have greatly increased the susceptibility of the soils to wind action. In dry years, the results have been most deplorable.

Wind erosion occurs when strong winds blow across soils with relatively dry surface layers. All kinds of soils and soil materials are affected, but silty and fine sandy soils generally are most quick to "blow." Sand particles may pile up in dunes, but the finer soil particles can be carried to great heights and for thousands of kilometers (Figure 17.43)—even from

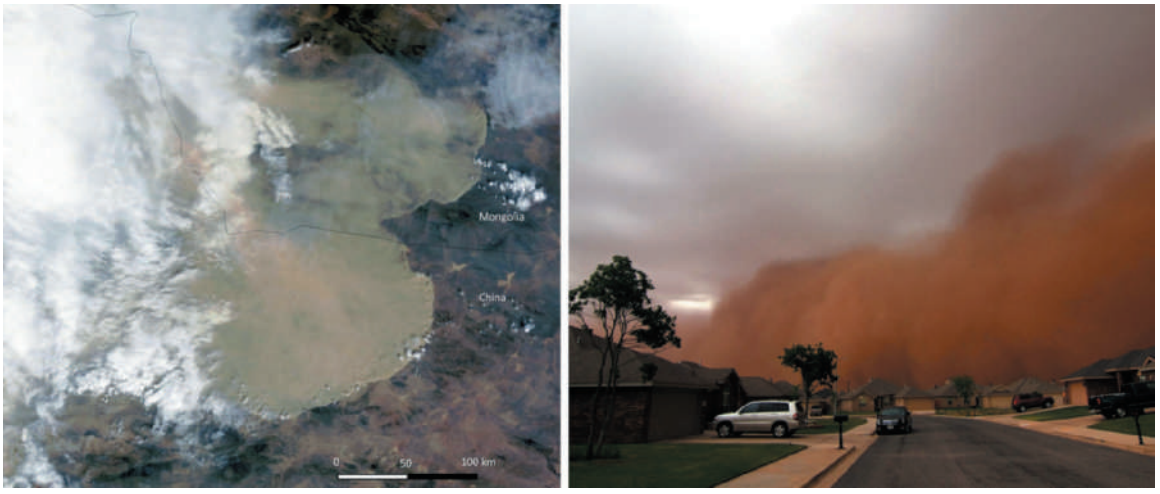

Figure 17.43 *Wind erosion can have drastic off-site effects on air quality and dust deposition. Damaging dust storms arise when high winds sweep across arid regions with unprotected soils. These storms can be regional in scale and the resulting dust deposition can have intercontinental effects. (Left) A giant wall of dust swallows large parts of China and Mongolia in a typical spring dust storm spawned from severe wind erosion in the loess deserts. (*Right*) A smaller, but still impressively damaging, dust storm bears down upon the town of Lubbock, in arid western Texas, USA.* (Photos courtesy of NASA (*left*) and Thomas Todd Lindley. (*right*))

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one continent, across the ocean, to another. A large dust storm originating in the southern Great Plains region of the United States in May 1934 had a special impact. Sending great clouds of silt, clay, and organic matter thousands of kilometers eastward and out over the Atlantic Ocean, the dust storm darkened the skies over Washington, D.C. and helped convince the U.S. Congress to fund a new government agency, the Soil Conservation Service. The far-reaching programs begun at this time are still combating soil erosion to this day (though the agency is now named the Natural Resources Conservation Service).

Wind erosion causes widespread damage, not only to the vegetation and soils of the eroding site, but also to anything that can be damaged by the abrasiveness of soil-laden wind, and finally to the off-site area where the eroded soil material settles back to earth (Figure 17.44). The on-site and off-site damages caused by wind erosion were discussed in Section 17.2.

The erosive force of the wind varies greatly among regions of the world and among seasons of the year within a specific location. For example, the Great Plains region of North America is subject to winds with 5–10 times the erosive force of the winds common in the eastern parts of Canada and the United States. In the Great Plains, the winds are most powerful in the winter season. In other regions, such as southern California and Arizona, high winds occur most commonly during the hot summers. Even in humid regions without an extended dry season, cultivated sandy and organic soils suffer significant wind erosion during winter fallow periods when their surface layer dries out and wind velocity is high. The movement of sand dunes along the Atlantic coast and the blowing of cultivated organic soils in New York and Michigan are examples.

Mechanics of Wind Erosion

Like water erosion, wind erosion involves three processes: (1) *detachment*, (2) *transportation*, and (3) *deposition.* The moving air, itself, results in some detachment of tiny soil grains from the granules or clods of which they are a part. However, when the moving air is laden with soil particles, its abrasive power is greatly increased. The impact of these rapidly moving grains dislodges other particles from soil clods and aggregates. These dislodged particles are now ready for one of the three modes of wind-induced transportation, depending mostly on their size.

Saltation. The first and most important mode of particle transportation is that of **saltation**, or the movement of soil by a series of short bounces along the ground surface (Figure 17.45). The particles remain fairly close to the ground as they bounce, seldom rising more than 30 cm or so. Depending on conditions, this process may account for 50–90% of the total movement of soil.

Soil Creep. Saltation also encourages **soil creep**, or the rolling and sliding along the surface of the larger particles. The bouncing particles carried by saltation strike larger particles and aggregate and accelerate their movement along the surface. Soil creep accounts for the movement of particles up to about 1.0 mm in diameter, which may amount to 5–25% of the total movement.

Figure 17.44 *Some effects of wind erosion. (Left) Soil eroded by wind during a single dust storm has piled up to a depth of nearly 1 m along a fencerow in semiarid Idaho, USA. The existing soil and plants are covered by deposits that are quite unproductive because the soil structure has been destroyed. Also, these deposits are subject to further movement when the wind direction changes. (Middle) Direct wind damage to a tomato crop in a sandy field in humid Delaware. The tomato plants are buried beneath windblown sandy soil. (Right) Young tomato fruits show damage incurred by sandblasting during a windstorm.* (Photos courtesy of Ray R. Weil)

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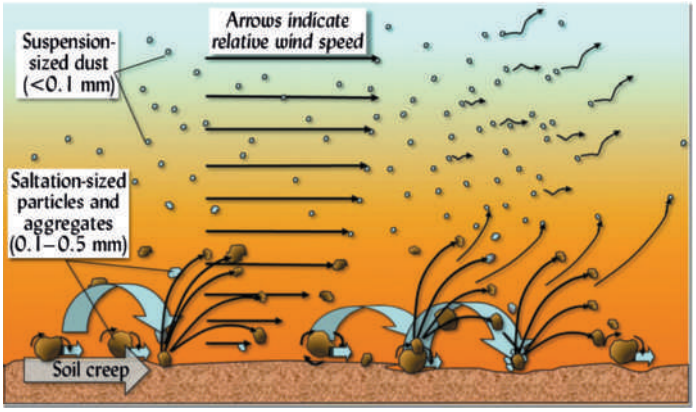

Figure 17.45 *How wind moves soil. Wind is blowing from left to right and is slowed somewhat by friction and obstructions near the soil surface (straight arrows). Fine particles are picked up and carried into the atmosphere, where they remain suspended until the wind slows. Medium sized particles or aggregates, being too large to be carried up in suspension, are bounced along the soil surface. When they strike larger soil aggregates, they release particles of various sizes. Fine particles become suspended in the air, while medium-sized particles continue to bounce along the surface. This process of medium-sized particles skipping along the surface is termed saltation. In a process termed soil creep, larger particles also roll along the soil surface, kept in motion by the wind itself and by collisions with the saltating particles.* (Diagram courtesy of Ray R. Weil)

Suspension. The most visually spectacular method of transporting soil particles is by movement in **suspension**. Here, dust particles of a fine-sand size and smaller are moved parallel to the ground surface and upward. Although some of them are carried at a height no greater than a few meters, the turbulent action of the wind results in other particles being carried kilometers upward into the atmosphere and many hundreds of kilometers horizontally. These particles return to the earth only when the wind subsides and/or when precipitation washes them down. Although it is the most striking manner of transportation, suspension seldom accounts for more than 40% of the total and is generally no more than about 15%.

Factors Affecting Wind Erosion

Wet soils do not blow because of the adhesion between water and soil particles. Dry winds generally lower the soil moisture content to below the wilting point before wind erosion takes place. Other factors that influence wind erosion are: (1) wind velocity and turbulence, (2) soil surface conditions, (3) soil characteristics, and (4) the nature and orientation of the vegetation.

Wind Velocity and Turbulence. The rate of wind movement, especially gusts having greater than average velocity, will influence erosion. The *threshold velocity*—the wind speed required to initiate soil movement—is usually about 25 km/h (7 m/s) (Table 17.12). At higher wind speeds, soil movement is proportional to the cube of the wind velocity. Thus, the quantity of

Table 17.12
THRESHOLD WIND VELOCITY, HEIGHT OF TRANSITION FROM SALTATION TO SUSPENSION, AND MASS OF SOIL CARRIED BY CREEP, SALTATION, AND SUSPENSION DURING FOUR WIND EROSION EPISODES ON CROPLAND AT BIG SPRING, TEXAS

Note that saltation accounted for most of the soil material moved, and that this movement mostly took place at heights of less than 30 cm above the soil surface. The location is semiarid, receiving an average of 470 mm of rainfall annually. The soil was a bare, smooth field of Amarillo fine sandy loam (Ustalfs).

Date	Threshold wind velocity, km/h	Height of transition from saltation to suspension, cm	Mass of soil material moved per width of wind path, kg/m			
			Creep	Saltation	Suspension	Total
22 January	24.5	22	0.87	13.33	0.72	14.92
5 February	25.2	22	7.68	142.9	13.43	164.01
14 March	25.9	28	0.43	15.9	3.98	20.31
21 March	28.1	27	0.10	2.41	0.30	2.80

Selected and modified from Fryrear and Saleh (1993).

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soil carried by wind increases dramatically as wind speeds above 30 km/h are reached. Wind turbulence also influences the capacity of the atmosphere to transport matter. Although the wind itself has some direct influence in picking up fine soil, the impact of wind-carried particles as they strike the soil (saltation) is probably more important.

Surface Roughness. Wind erosion is less severe where the soil surface is rough. This roughness can be obtained by proper tillage methods, which create large clods or ridges. Leaving a stubble mulch (see Section 6.4) is an even more effective way of reducing wind-borne soil losses.

Soil Properties. In addition to moisture content, wind erosion is also influenced by: (1) mechanical stability of soil clods and aggregates, (2) stability of soil crusts, (3) bulk density, and (4) size of erodible soil fractions. Some clods resist the abrasive action of wind-carried particles. If a soil crust resulting from a previous rain is present, it, too, may be able to withstand the wind's erosive power. The presence of clay, organic matter, and other cementing agents is also important in helping clods and aggregates resist abrasion. This is one reason why sandy soils, which are low in such agents, are so easily eroded by wind. Because they participate in saltation, soil particles or aggregates about 0.1 mm in diameter are more erodible than those larger or smaller in size.

Vegetation. Vegetation or stubble mulch will reduce wind erosion hazards, especially if rows run perpendicular to the prevailing wind direction. This effectively slows wind movement near the soil surface. In addition, plant roots help bind the soil and make it less susceptible to wind damage. Biological crusts are important in protecting desert soils from erosion.

17.12 PREDICTING AND CONTROLLING WIND EROSION

As for soil erosion by water, mathematical models or equations have also been developed to predict soil loss from the action of wind. The wind erosion prediction equation (WEQ) has been in use since the late 1960s:

$$E = f(I \times C \times K \times L \times V) \tag{17.2}$$

The predicted amount of soil loss by wind erosion E is a function f of five factors:

I = soil erodibility factor
C = climate factor
K = soil-ridge-roughness factor
L = width of field factor
V = vegetative cover factor

The WEQ involves the major factors that determine the severity of the erosion, but it also considers how these factors interact with each other. Consequently, it is not as simple as is the USLE for water erosion. Evidence of the interaction among factors is seen in Figure 17.46. The **soil erodibility factor** I relates to the properties of the soil and to the degree of slope of the site in question. The **soil-ridge-roughness** factor K takes into consideration the cloddiness of the soil surface, vegetative cover V, and ridges on the soil surface. The **climatic factor** C involves wind velocity, soil temperature, and precipitation (which helps control soil moisture). The **width of field factor** L is the width of a field in the downwind direction. Naturally, the width changes as the direction of the wind changes, so the prevailing wind direction is generally used. The **vegetative cover** V relates not only to the degree of soil surface covered with residues, but to the nature of the cover—whether it is living or dead, still standing, or flat on the ground. The situation may be complicated by interactions between two or more of these wind erosion factors. For instance, a drier climate may result in less vegetative cover and therefore more wind erosion (Figure 17.46)

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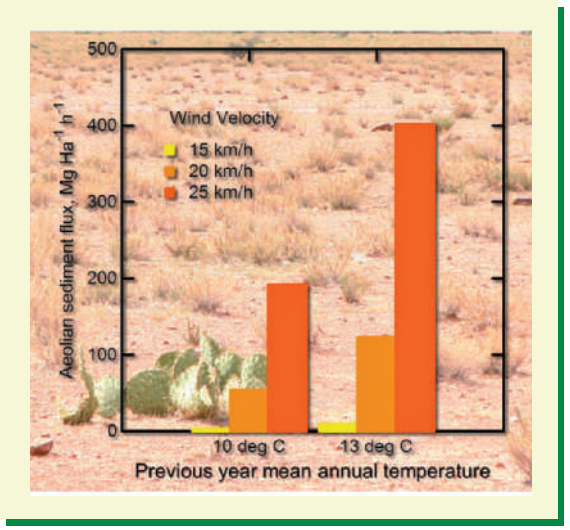

Figure 17.46 *Interaction of climate and vegetative cover can affect the amount of wind erosion (aeolian sediment flux). An increase in mean temperature on the Colorado plateau of 3 °C resulted in greater soil drying that decreased vegetation cover from 45% to 20% of the ground surface. In turn, this climate-induced reduction in vegetative cover more than doubled the amount of erosion caused by high winds the following year.* [Graph based on data selected from Munson et al. (2011)]

A revised, more complex, and more accurate computer-based prediction model has been developed, and is known as the **revised wind erosion equation (RWEQ)**. It is still an empirical model based on many site-years of research to characterize the relationship between observable conditions and resulting wind erosion severity. Table 17.13 outlines the factors taken into consideration by RWEQ, which (like RUSLE) calculates the erosion hazard during 15-day intervals throughout the year. For each interval of time, the RWEQ makes adjustments in the residue, soil erodibility, and soil roughness parameters, based on the input information about management operations and weather conditions. For example, it assumes that residues decompose over time, tillage operations flatten standing residues, and rainfall reduces soil roughness by slaking soil clods.

Scientists and engineers around the world are also cooperating in the continual development of a much more complex process-based model known as the **Wind Erosion Prediction System (WEPS)**. Like its water erosion sister, WEPP, this computer program simulates all the basic processes of wind interaction with soil. Scientists are continually improving the model and testing its predictions against data observed in the real world. The USDA makes this model freely available online (http://www.weru.ksu.edu/weps/wepshome.html). However, to run complex process–based models like WEPP and WEPS one must supply a great deal of information about every aspect of the site on which erosion is to be predicted. Therefore, the simpler, tried-and-true empirical models also continue to be in widespread use.

Control of Wind Erosion

Wind erosion is more easily prevented than controlled once it has begun. Therefore, a field or landscape should be assessed to determine the most vulnerable spots; those should receive immediate attention and close observation to avoid the onset of wind erosion. For example, a semiarid landscape may support enough vegetation to prevent wind erosion, except on hilltops exposed to the greatest wind velocities. If the most vulnerable soils are not protected, small exposed areas may begin to blow, leading to saltation damage to adjacent microsites and thus to accelerating erosion that quickly degrades the entire landscape. Rangeland blowouts, knolls, patches of fine sandy soils, and tire tracks or foot paths may be among the areas most vulnerable to wind. When erosive conditions (dry soils and high winds) are expected, taking preventative measures on these vulnerable areas may stop a major problem before it gets started. The following paragraphs suggest some of the types of measures that may be taken to prevent or control wind erosions.

Soil Moisture. The factors included in the wind erosion equation suggest approaches that can be taken to reduce wind erosion. For example, since soil moisture increases cohesiveness, the wind speed required to detach soil particles increases dramatically as soil moisture increases.

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Table 17.13
SOME FACTORS INTEGRATED IN THE REVISED WIND EROSION EQUATION (RWEQ) MODEL
The RWEQ program calculates values for each factor for each 15-day period during the year. It also calculates interactions; that is, it uses the value of one factor to modify other factors.

Model factor	Subfactor terms in the model	Comments
Weather factor	Weather factor *WF*; includes terms for wind velocity, direction, air temperature, solar radiation, rainfall, and snow cover.	Modified by other factors such as soil wetness.
Soil factors	Erodible fraction *EF*; fraction smaller than 0.84 mm diameter.	Based on sand, silt, organic matter, and rock cover.
	Soil crust factor *SCF*.	
	Surface roughness *SR*; a random component due to clods and/or an oriented component due to ridges.	
	Soil wetness *SW*.	
		Induced by rainfall, eliminated by tillage.
		Interacts with rainfall and tillage.
		Computed from rainfall minus evapotranspiration.
Tillage factor	Tillage factor *TF*; depends on type of implement, soil conditions, timing, and so forth.	Modifies surface roughness, crust factor, and so forth.
Hill factor	Hill factor *HF*; slope gradients and length input.	Affects wind speed (high going upslope, lower going down).
Irrigation factor	Irrigation factor *IR*.	Equivalent to added rainfall.
Crops factor	Flat residue *SLRf* factor.	Soil cover by residues lying on the surface is estimated for each crop, including changes over time due to decay, and so forth.
	Standing residue *SLRs*; depends on crop, harvest height, plant density, and so forth.	Standing residues reduce the wind speed at the soil surface. Decay is slower than for flat residues.
	Crop canopy factor *SLRc*.	Changes daily with crop growth.
Barriers	Barriers (e.g., tree windbreaks); includes orientation, density, height, spacing.	Reduce leeward wind velocity.

Based on information in Fryrear et al. (2000).

Therefore, where irrigation water is available, an effective protective practice is to moisten the soil surface when high winds are predicted. Unfortunately, most wind erosion occurs in dry regions without available irrigation.

Soil Cover. Plant cover effectively protects soil from blowing, especially if the plant roots are well established. Crop rotations that include cover crops can greatly diminish wind erosion. In semiarid areas, however, many farmers attempt to conserve soil moisture by leaving some of their fields fallow (bare of water-using vegetation) during alternate summer seasons. Fallow, especially if practiced with tillage that maintains a smooth, bare soil surface can greatly increase the susceptibility to wind erosion. Consequently, if farmers feel they must leave fields in fallow to conserve profile moisture, it is critical to control wind erosion by employing means other than growing vegetative cover.

Tillage. Certain conservation tillage practices described in Section 17.6 were used for wind erosion control long before they became popular as water erosion control practices. No-till practices that leave the soil in a consolidated but biopore riddled mass covered by growing vegetation or anchored residues is the best protection available for cropland. On tilled cropland, a rough surface and at least partial some vegetative or residue cover can be maintained

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by using appropriate tillage practices. Ideally, both living and dead vegetation should be well anchored into the soil to prevent it from blowing away. Stubble mulching has proven to be an effective practice for this purpose (see Section 6.4).

The effect of tillage depends not only on the type of implement used, but also on the timing of the tillage operation. Tillage can greatly reduce wind erosion if it is done while there is sufficient soil water to cause large clods to form. Tillage on a dry soil may produce a fine, dusty surface that aggravates the erosion problem. Tillage to provide for a cloddy surface condition should be at right angles to the prevailing winds. Likewise, strip-cropping and alternate strips of cropped and fallowed land should be perpendicular to the wind.

Barriers. Barriers or *windbreaks* such as tree shelter belts (Figure 17.47*a*,*b*) are effective in reducing wind velocities for short distances and for trapping drifting soil. Significant protection against wind erosion extends to a distance of about ten times the height of the barrier (Figure 17.47*e*). Tree windbreaks and rows of tenacious shrubs are especially effective. Rows of grasses are often used to form microwindbreaks. For example, narrow strips of cereal rye, planted in across the field perpendicular to the prevailing wind, are sometimes used on peat lands and on sandy soils (see Figure 17.46*c*,*d*). Narrow rows of perennial grasses (e.g., tall wheatgrass) have been useful for a combination of wind erosion control and capturing of winter snows in the Northern Great Plains.

Not all windbreaks are living; picket fences and burlap screens, though less efficient as windbreaks than trees, are often preferred because they can be moved from place to place as crops and cropping practices are varied. A particularly successful nonliving microwindbreak technology has been successfully developed and deployed to control blowing sands and aid in reforestation in the arid northwest of China (Figure 17.48).

17.13 TILLAGE EROSION

Globally, wind and water are the major agents of soil erosion, commonly abetted on cropland by tillage that leaves the soil exposed without protective cover. In addition, on tilled crop fields, the action of tillage itself is an important third agent of erosion.

Movement of Soil by Tillage

Any tillage operation will loosen and move soil. Some types of tillage, such as moldboard plowing and disk harrowing pick up and invert large quantities of soil. Some, such as the chisel plow, spread it over distances of several meters. Even field operations such as shallow

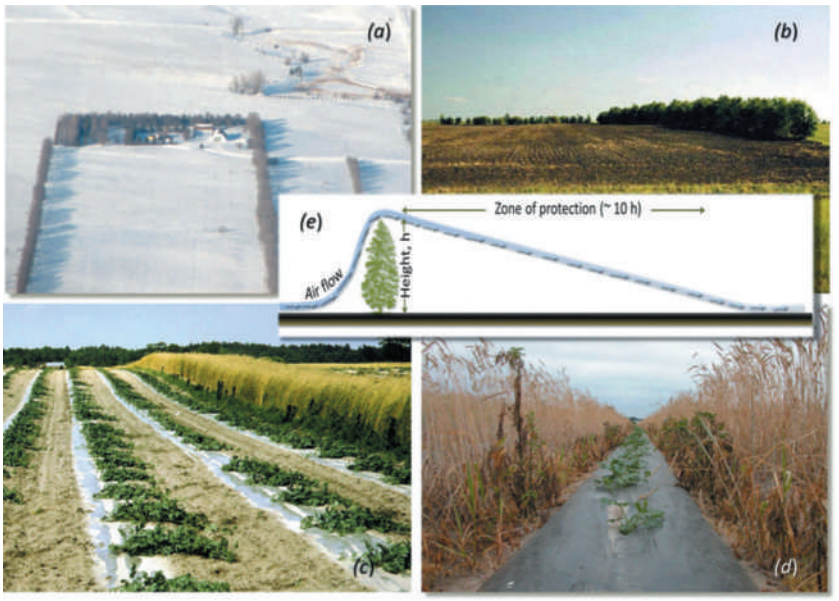

Figure 17.47 *Wind breaks to reduce wind erosion. (a,b) Trees make good windbreaks and add beauty to a North Dakota, USA, farm homestead. (e) The effect of a windbreak on wind velocity. The wind is deflected upward by the trees and is slowed down even before reaching them. On the leeward side further reduction occurs; the effect being felt as far as ten times the height of the trees. (c,d) Narrow strips of cereal rye act as miniature windbreaks to protect watermelons from wind erosion on a loamy sand on the mid-Atlantic coastal plain in the United States.* [Photos courtesy of Ray R. Weil, diagram based on concepts in Tatarko (2010)]

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Figure 17.48 Ecological engineers use straw checkerboards for wind erosion control, reforestation and improvement of sandy soils in arid Ningxia Province, China. (a) Windblown sand has completely degraded a once forested area, but reforestation efforts can be seen as the dark areas on the sand dunes. (b) Rice straw produced in irrigated river valleys is trucked into the desert where workers use shovels to anchor it into the loose sand to form squares about 1 m on a side. (c) A tiny tree seedling will be planted in each rice straw square, which remains substantially intact and inhibits wind erosion for several decades. (d) Some 20 years after planting, the trees are growing but the straw has mostly disappeared. Dust trapped by the straw checkerboard changed soil texture from 99% sand to only 80%–90% sand and 10%–20% silt and clay. [Information based on Li et al. (2006). Photos courtesy of Ray R. Weil]

Figure 17.49 *A chisel plow in action. Tillage implements such as this loosen and move large quantities of soil, some of which is thrown into the air. The amount of a certain soil that will be moved and the distance it is moved depend on the design of the implement, depth of tillage, and speed of travel. The soil moves mainly in the direction of travel, but will move much farther when travel is downslope so gravity assists the movement. When tillage is upslope, gravity hinders the forward movement of soil.* (Photo courtesy of Ray R. Weil)

cultivation to control weeds or planting seed may disturb and move substantial quantities of soil. The amount of soil moved and the distance it is moved depend on the design of the implement, the depth of tillage, and the speed of travel (as well as the type of soil). High speed tillage especially tends to throw soil into the air as well as push it forward; chisel plowing (Figure 17.49) and vertical tillage (Figure 17.25) are examples.

Soil moves mainly in the direction of tillage. When the tillage implement is traveling upslope, gravity hinders the forward movement of soil. Soil will move much farther when the implement is traveling downslope and the force of gravity assists in moving the soil forward. Even when tillage is on the contour, soil thrown sideways will travel farther downslope than upslope. Therefore, the net movement of soil by tillage is always downslope. In this process, topsoil is removed from the hilltops and accumulates in the valleys, thus gradually leveling the landscape (Figure 17.50). Once the A horizon material is mostly scalped off the hilltops continued tillage will mix subsoil material into the till layer. This action often changes the color of the soil exposed on the hilltops (Figure 17.6, *left*).

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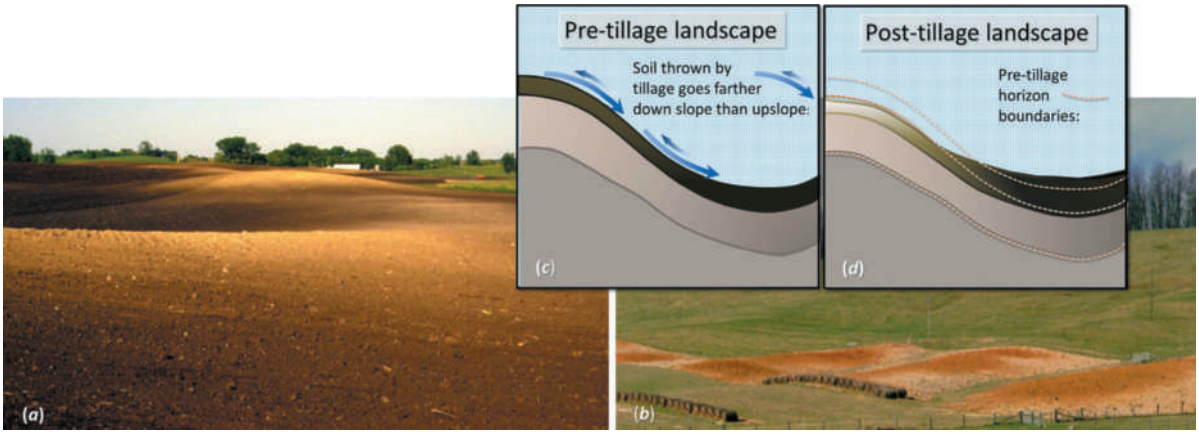

Figure 17.50 *The exposure of B horizon soil on the crests of small hills in cultivated landscapes is largely due to tillage erosion. (*Left*) The whitish calcareous subsoil material from Mollisols is mixed into the plow layer of a conventionally tilled field in sub-humid Minnesota, USA. (*Right*) Reddish B horizon material is likewise mixed into the hilltop plow layer of Ultisols in a strip-cropped field in humid Virginia, USA. The diagram illustrates how tillage scalps the hilltops by throwing soil farther downslope than upslope, resulting in a net movement of soil downslope and gradual leveling of the landscape.* (Diagram courtesy of Ray R. Weil. Photos courtesy of Ray R. Weil (*right*) and David A. Lobb, University of Manitoba (*left*))

Quantification of Tillage Erosion

There are several models of tillage erosion that are based on the relationship between the amounts of soil moved by tillage in the upslope and downslope directions and slope gradient. The most general of these models is the Tillage Erosion Risk Indicator model (TillERI), which in its simplest form considers the product of a tillage implement factor and a landscape factor

$$A_t = E_t \times E_l \tag{17.3}$$

Here A_t = annual *rate of soil movement* downslope due to tillage erosion (Mg ha^{-1} y^{-1}); E_t = the *erosivity* of tillage operations (kg · $\%^{-1}$ · m^{-1} · y^{-1}) expressed as kg of soil moved annually per m of tillage width and percentage slope inclination (where a slope of 45° = 100%); and E_l = the *erodibility* of the landscape (% · m · ha^{-1}).

The landscape erodibility factor, E_l, is based on slope length (l) and slope gradient (s) factor values and can be determined using the topographic data from the revised universal soil loss equation (RUSLE). Tillage erosion is most active on landscapes with many small hills characterized by short, steep slopes (such as those pictured in Figure 17.50). Soil properties such as water content, texture, and structure also influence the vulnerability of a landscape to tillage erosion.

The erosivity of tillage operations E_t is a function of four factors (I_d, I_o, I_m, I_b) related to the tillage implement and how it is used. The first implement factor I_d represents the ***d**esign* of the tillage implement, i.e., the type, size, number, and angle of coulters, tines, or other steel parts that interact with the soil. The second factor I_o represents the mode of ***o**peration* of the implement, namely, the speed and depth of tillage. The third factor I_m represents the ***m**atch* between the available power of the tractor and the power required to draw the implement. Finally, the fourth factor I_b represents the operator ***b**ehavior*, i.e., how steadily and in what patterns (across or up and down the slopes) the farmer drives across the field.

Compared to that devoted to water and wind erosion, very little research has been directed to determine factor values for tillage erosion. Values for E_t per tillage pass are typically in the range of 0.5–5 kg soil per m of tillage width per percent slope inclination. Considering these four factors that contribute to the tillage erosivity, it is not surprising that values for E_t vary widely from one research study to another, even when the tillage operation is very similar (e.g., chisel plowing at a given speed and depth). However, the few measurements that have been made suggest that certain high speed conservation tillage operations, such as strip-till planting may cause nearly as much tillage erosion as primary tillage operations like mold

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board or chisel plowing. How much and how far soil is moved is important, but it is the variation of these within the landscape (e.g., the difference between tillage moving uphill and that going down) that causes soil erosion; certain operations, particularly those carried out at high speed, tend to have much greater variation in soil movement (Table 17.14).

Annual rates of erosion by tillage have been reported in the range of 20–50 Mg ha^{-1} for mechanized farming on hummocky landscapes and as high as 100–200 Mg ha^{-1} for cultivated steep mountainsides where tillage was powered by draft animals or human being with soil pulled only in the downslope direction. Rates of any type of erosion are difficult to put in a whole landscape perspective since parts of the landscape lose soil while other parts gain, and only a small fraction (the delivery ratio, Section 17.3) of the soil moved by erosion is exported from the landscape by streamflow or in the air. The export of soil out of the watershed, or even off the field, is generally much larger for soil moved by water or wind than for soil moved by tillage. Another important difference among the agents of soil erosion is the quality of the material deposited in the downslope positions (Figure 17.51).

In our discussion of wind and water erosion, we emphasized that by the time the eroded material is deposited downwind, downslope, or downstream it has become mere dust or muddy sediment. The deposited material has little value as productive soil because transport by wind and water destroys soil structure, segregates out the various particle sizes, and often removes organic matter and nutrients. In contrast, the material moved downslope by tillage is still productive soil when it accumulates in the low lying, concave parts of the landscape. That is, the soil eroded by tillage is not mere sediment, but generally retains most of the desirable physical, chemical, and biological properties of a productive soil. Therefore, where movement by tillage is the main erosion process, the potential may exist to remediate the erosion damage using mechanized land scrapers that can efficiently move many Mg per hectare of eroded soil back upslope to restore the thickness of productive soil on the hilltops. In fact, studies in western Canada suggest that such soil restoration might be economically viable under certain circumstances.

Table 17.14
EROSIVITY CHARACTERISTICS OF SELECTED TILLAGE IMPLEMENTS AND OPERATIONS
Types of tillage implements are listed from most to least erosive. Note that planting and harvesting root crops like potato are highly erosive operations. The values here are for a single pass of the implement, except where indicated. The research from which these values were derived was conducted in several provinces in Canada and somewhat different values could be expected under different conditions.

Type of implement	Type of operation	T_M,[a] kg m^{-1}	E_t,[b] kg m^{-1} $\%^{-1}$
		kg m^{-1}	kg m^{-1} $\%^{-1}$
Potato planter + 2 passes with hiller	Conventional tillage	117	3.6
Potato harvester	Conventional tillage	70	3.0
Moldboard plow	Primary tillage	60	1.4
Chisel plow	Primary tillage	60	1.5
Tandem disk	Secondary tillage	50	2.0
Offset disk	Secondary tillage	34	1.8
Cultivator plus air-seeder with knives	Conventional tillage	35	1.0
Cultivator	Secondary tillage	46	0.2
Air-seeder with knives	Conventional tillage	4	0.1
Air-seeder with knives	No-till	8	0.1
Air-seeder with sweeps	No-till	30	1.0

[a]The movement of soil which would occur on a flat ground.
[b]The movement of soil due to slope gradient.
Data selected, recalculated and rearranged from Lobb (2008).

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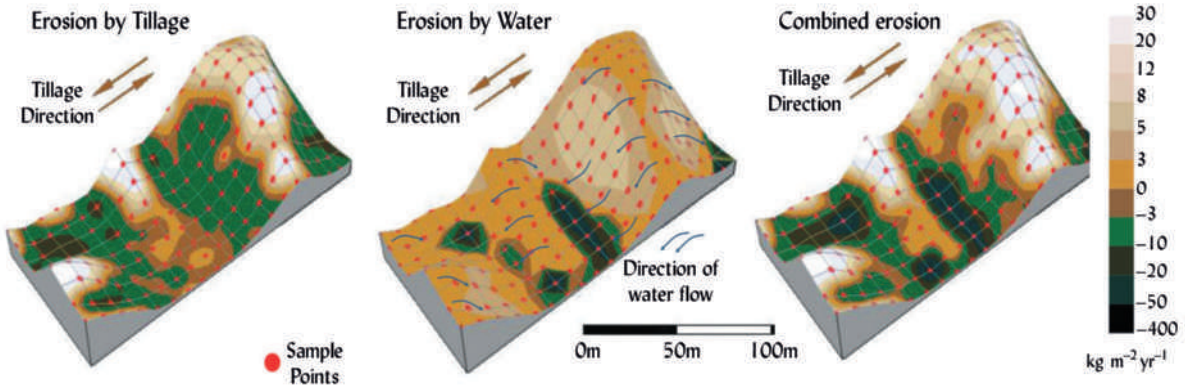

Figure 17.51 *In certain cultivated landscapes in humid regions, more soil has been shown to move downhill by tillage erosion than by water erosion. Likewise, in semiarid regions tillage erosion may move more soil than erosion by wind. The block diagrams provide maps of where models showed soil was lost and gained during a seven-year period of cropping with conventional tillage on a hilly field in Ontario, Canada. The red dots represent the locations where samples were obtained to assess soil loss or gain. The dark green represents annual soil gains of up to 400 kg m^{-2}, while the light colors show annual soil loss of up to 20 kg m^{-2}. Note that soil removal by water erosion was greatest (lightest colors) mainly from the steepest side-slopes (*middle diagram*). In contrast, tillage erosion removed the most soil from the crest of the hillocks (*left diagram*). The combined effects from both agents of erosion (*right diagram*) show that most overall soil loss was from the knoll summits as is characteristic of tillage erosion.* [Diagrams courtesy of David Lobb, University of Manitoba, based on Li et al. (2011)]

17.14 LAND CAPABILITY CLASSIFICATION AS A GUIDE TO CONSERVATION

The land capability classification system devised by the U.S. Department of Agriculture has been used since the 1950s to assess the appropriate uses of various types of land. It is especially helpful in identifying land uses and management practices that can minimize soil erosion by water.

The system uses eight **land capability classes** to indicate the *degree* of limitation imposed on land uses (Figure 17.52), with Class I the least limited and Class VIII the most limited. Each land-use class may have four subclasses that indicate the *type* of limitation encountered: risks of erosion (e); wetness, drainage, or flooding (w); root-zone limitations, such as acidity, density, and shallowness (s); and climatic limitations, such as a short growing season (c). The erosion (e) subclasses are the most common; for example, Class IIe land is slightly susceptible to erosion, while Class VIIe is extremely susceptible. Figure 17.53 shows the appropriate intensity of use allowable for each of these land capability classes if erosion losses (or problems associated with the other subclasses) are to be avoided. Table 17.15 indicates the extent of major limitations on land use in the United States with erosion and sedimentation

Figure 17.52 *Several land capability classes in the Lockyer Valley of Queensland, Australia. A range is shown from the nearly level land in the center (Class I), which can be cropped intensively, to the badly eroded hillsides (Classes VI and VII). Although topography and erosion hazards are emphasized here, it should be remembered that other factors—drainage, stoniness, and droughtiness—also limit soil usage and help determine the land capability class.* (Figure courtesy of Ray R. Weil)

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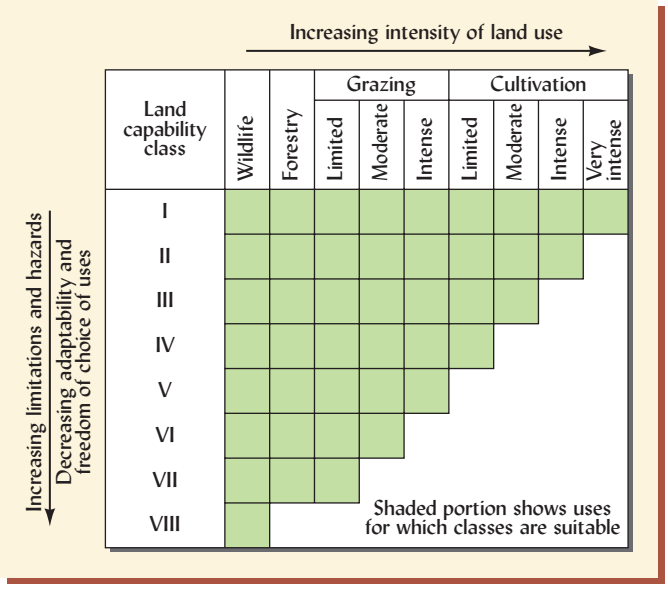

Figure 17.53 *Intensity with which each land capability class can be used with safety. Note the increasing limitations on the safe uses of the land as one moves from Class I to Class VIII.* [Modified from Hockensmith and Steele (1949)]

Table 17.15
PERCENTAGE OF U.S. LAND WITH MAJOR LIMITATIONS BY LAND-USE CAPABILITY CLASS
Erosion and sedimentation are widespread limitations, but wetness and shallowness also limit land uses.

	Percentage of land with indicated major limitation			
LUC class	Erosion and sedimentation	Wetness	Shallowness	Climate hazards
II	51	34	8	7
III	67	22	9	2
IV	69	16	14	1
VI	62	8	26	3
VII	47	6	45	2
Total	59	18	21	3

Calculated from USDA (1994).

problems limiting land use for nearly 60% of the land. Excessive wetness and shallowness are each problems on about 20% of the land.

Class I lands are nearly level with deep, well-drained soils and therefore little or no limitations on agricultural uses. Classes II, III, and IV can be used for agriculture, but with increasing limitations and requirements for remedial or protective measures. Class V lands are generally not suited to crop production because of factors other than erosion hazards, including: (1) frequent flooding, (2) shortness of growing season, (3) stoniness, (4) waterlogged soils where drainage is not feasible. Often, pastures can be of good quality on this class of land. Class VI and VII lands are highly susceptible to erosion or other limitations and the choices of land uses severally restricted, but often can provide good grazing or timber lands under proper management. Class VIII land is best left undisturbed in natural vegetation; it includes sand beaches, river wash, and rock outcrops and extremely steep terrain.

The land-use capability classification scheme illustrates the practical value of combining knowledge of soil properties and behavior with the geographic information supplied by soil

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surveys (see Section 19.7). The many soils delineated on a map by the soil surveyor are viewed in terms of their safest and best long-time use. The eight land capability classes have become the starting point in the development of land-use plans that promote wise use and conservation of the land resource by thousands of farmers, ranchers, and other landowners.

17.15 PROGRESS IN SOIL CONSERVATION

Soil Erosion

Soil erosion in the United States accelerated when the first European settlers chopped down trees and began to farm the sloping lands of the humid eastern part of the country. Soil erosion was a factor in the declining productivity of these lands that, in time, led to their abandonment and the westward migration of people in search of new farmlands.

It wasn't until the worldwide depression and widespread droughts of the early 1930s accentuated rural poverty and displaced millions of people that governments began to pay attention to the rapid deterioration of soils. In 1930, Dr. H. H. Bennett and associates recognized the damage being done and obtained U.S. government support for erosion-control efforts. Since then, considerable reductions in erosion have been achieved (see, e.g., Figure 17.54).

During the 1940s and 1950s such physical practices as contour strips, terraces, and windbreaks were installed with much persuasion and assistance from government agencies. Some of this progress was reversed as the terraces and windbreaks appeared to stand in the way of the "fence row to fence row" all-out crop production policies of the 1970s. But, since 1982 rather remarkable progress has been achieved in reducing soil erosion (Figure 17.55), largely as a result of two factors: (1) the spread of conservation tillage (see Section 17.6), and (2) the implementation of land-use changes as part of the conservation reserve program (CRP). Progress continues to be made on both fronts.

However, about one-third of the cultivated cropland in the United States is still losing more than 11 Mg/ha/yr, the maximum loss that can be sustained without serious loss of productivity on most soils. After some 80 years of soil conservation efforts, soil erosion is still a major problem on about half the cropland of the United States and in much of the world the problem has actually worsened.

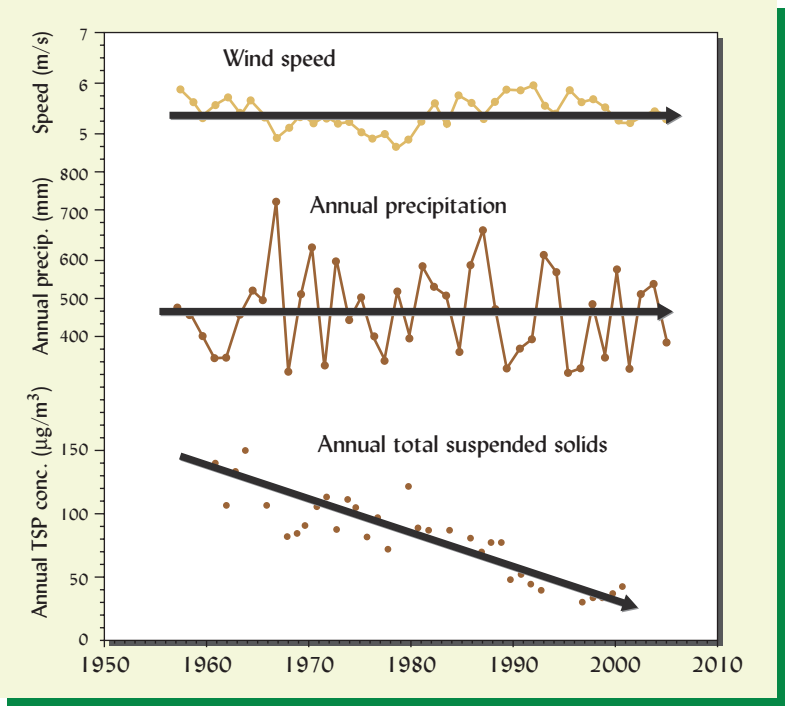

Figure 17.54 *Wind-blown dust (total suspended solids, TSP) has declined significantly since 1960 in the Southern High Plains of Texas in the United States (lower trend arrow). Records show that neither average wind speed nor the average precipitation changed during this period (upper two trend arrows), so the decline in wind erosion was not due to less erosive climatic conditions. Minor changes occurred in land use with some cropland being converted to rangeland (not shown), but the area involved was far too small to account for the reductions in dust. Most likely it was the widespread adoption of conservation tillage and other improved agricultural practices that were responsible for the downward trends in wind erosion activity and dust emissions (TSP) during this period.* [Compiled from figures in Stout and Lee (2003)]

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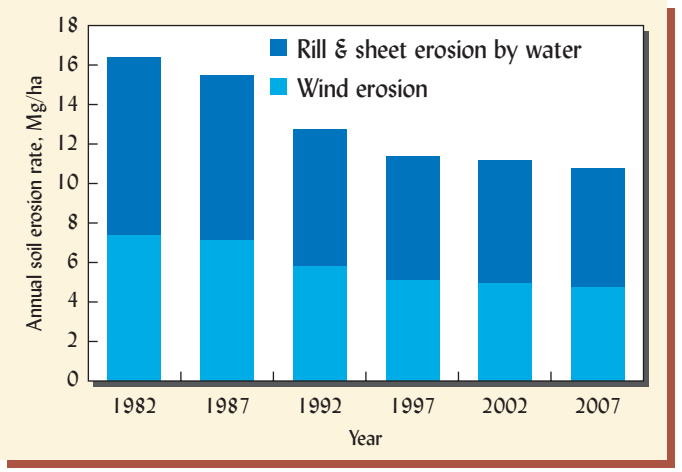

Figure 17.55 *Average rates of soil loss by water and wind erosion in the United States from 1982 to 2007. Farmer adoption of conservation tillage practices along with the Conservation Reserve Program likely account for the nearly 40% reduction in rate of combined wind and water erosion between 1982 and 1997. The following decade saw little additional progress.* [Calculated from data in USDA-NRCS (2006)]

The Conservation Reserve Program

A major part (about 60%) of the reduction in soil erosion experienced in the United States since 1982 is due to government programs that have paid farmers to shift some land from crops to native perennial vegetation. Establishing grasses or trees on these former croplands reduced the sheet and rill erosion from an average of 19.3 to 1.3 Mg/ha and the wind erosion from 24 to 2.9 Mg/ha. Between 1982 and 2006, 14 million ha of cropland were diverted to such noncultivated uses through the **CRP**. The CRP is designed to target **highly erodible land (HEL)**[15] and other environmentally sensitive areas such as riparian zones.

The CRP is basically an arrangement by which the U.S. taxpayers pay rent to farmers to forego cropping part of their farmland and instead plant grass or trees on it (more rent is paid for trees). The rental agreements (leases) run for 10–15 years, during which time the land is undisturbed. The benefits to the nation have been evident, not only in greatly reduced soil losses and sediment pollution, but also in a dramatic upswing in wildlife as bird and animal populations take advantage of the newly restored habitat. Where strips of land along streams (riparian zone buffers) have been incorporated into the CRP, water-quality benefits have also been amplified. The benefits of carbon sequestration (see Section 12.10) to mitigate climate change have also been significant.

Conservation Management to Enhance Soil Quality

In a broader sense, conservation management practices are those that improve soil quality in more ways than just by protecting the soil from erosion. Properties that indicate the level of soil quality, especially those associated with soil organic matter, can be enhanced by such conservation measures as minimizing tillage, maximizing residue cover of the soil surface, providing for diversity of plant types, keeping soil under grass sod vegetation for at least part of the time, adding organic amendments where practical, and maintaining balanced soil fertility. Improved soil quality, in turn, enhances the soil's capacity to support plants, resist erosion, prevent environmental contamination, and conserve water. Conversation management therefore can lead to the upward spiral of soil and environmental improvement referred to in Section 17.1.

Adapting Soil Conservation to the Needs of Resource-Poor Farmers

As satisfying as the progress of the past decades has been, soil losses by erosion are still much too high. Continued efforts must be made to protect the soil and to hold it in place. In the

[15]Highly erodible land is defined by the USDA Natural Resources Conservation Service as land for which the USLE predicts that soil loss on bare, unprotected soil would be eight times the T value for that soil: $R \times K \times LS \geq 8T$.

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United States, some 30 million ha of highly erodible cropland continue to lose an average of more than 15 Mg/ha of soil each year from water erosion, and an equal amount from wind erosion. In spite of remarkable progress, conservation tillage systems have *not* been adopted for more than half of the nation's cropland. And no one knows what will happen to the CRP lands when the rental leases expire. The battle to bring erosion under control has just begun, not only in the United States but throughout the world.

In much of the world, so little land is available to each farmer for food production that nations cannot afford the luxury of following the land-use capability classification recommendations as outlined in Section 17.13. Many farmers must use *all* land capable of food production simply to stave off starvation and impoverishment. These farmers often realize that farming erodible land jeopardizes their future livelihood and that of their children, but they see no choice. It is imperative to either find nonagricultural employment for these people or to find farming systems that are sustainable on these erodible lands.

Fortunately, some farmers and scientists have developed, through long traditions of adaptation or through innovation and research, farming systems that *can* produce food and profits while conserving such erodible soil resources. Examples include the traditional Kandy Home Gardens of Sri Lanka's humid mountains, in which a rain forest–like mixed stand of tall fruit and nut trees is combined with an understory of pepper vines, coffee bushes, and spice plants to provide valuable harvests while keeping the soil under perennial vegetative protection. Another example comes from Central America, where farmers have learned to plant thick stands of velvet bean (*Mucuna*) or other viney legumes that can be chopped down by machete to leave a soil-protecting, water-conserving, weed-inhibiting mulch on steep farmlands. In Asia, steep lands have been carefully terraced in ways that allow production of food, even paddy rice, on very steep land without causing significant erosion.

Many examples from the United States and around the world make it clear that when governments cajole, pay, or force farmers into installing soil conservation measures on their land, the results are unlikely to be long-lasting. Usually, farmers will abandon the unwanted practices as soon as the pressure is off. On the other hand, if scientists and conservationists work *with* farmers to help them develop and adapt conservation systems that the farmers feel are of benefit to their families and their land, then effective and lasting progress can be made. Experience with conservation tillage systems in the United States, mulch farming systems in Central America, and vegetative contour barriers in Asia have shown that farmers can help develop practices that are good for their land and for their profits: a win-win situation.

17.16 CONCLUSION

Accelerated soil erosion is one of the most critical environmental and social problems facing humanity today. Erosion degrades soils, making them less capable of producing the plants on which animals and people depend. Equally important, erosion causes great damage downstream in reservoirs, lakes, waterways, harbors, and municipal water supplies. Wind erosion also causes fugitive dust that may be very harmful to human health. Tillage itself is a third agent of erosion on cropland and may move more soil than wind and water combined in some cases.

Nearly 4 billion Mg of soil is eroded each year on land in the United States alone. Half of this erosion occurs on the nation's croplands, and the remainder on harvested timber areas, rangelands, and construction sites. Some one-third of the cropland still suffers from erosion that exceeds levels thought to be tolerable.

Water carries away most of the sediment in humid areas by sheet and rill erosion. Gullies created by infrequent, but violent, storms account for much of the erosion in drier areas. Wind is the primary erosion agent in many drier areas, especially where the soil is bare and low in moisture during the season when strong winds blow. Tillage erosion is most damaging on cultivated land with hummocky topography.

Protecting soil from the ravages of wind or water is by far the most effective way to constrain erosion. In croplands and forests, such protection is due mainly to the cover of plants and their residues. Conservation tillage practices maintain vegetative cover on at least 30% of

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the soil surface, and the widening adoption of these practices has contributed to the significant reductions in soil erosion achieved over the past two decades. Crop rotations that include sod and close-growing crops, coupled with such practices as contour tillage, strip-cropping, and terracing, also help combat erosion on farmland.

In forested areas, most erosion is associated with timber-harvesting practices and forest road construction. For the sake of future forest productivity and current water quality, foresters must become more selective in their harvest practices and invest more in proper road construction.

Construction sites for roads, buildings, and other engineering projects lay bare many scattered areas of soils that add up to a serious erosion problem. Control of sediment from construction sites requires carefully phased land clearing, along with vegetative and artificial soil covers, and installation of various barriers and sediment-holding ponds. These measures may be expensive to implement, but the costs to society that result when sediment is not controlled are too high to ignore. Once construction is completed, erosion rates on urban areas are commonly as low as those on areas under undisturbed native vegetation.

Erosion-control systems must be developed in collaboration with those who use the land, and especially the poor, for whom immediate needs must overshadow concerns for the future. As put succinctly in *The River*,[16] a classic 1930s documentary film produced during the rebirth of American soil erosion consciousness, "Poor land makes poor people, and poor people make poor land."

STUDY QUESTIONS

1. Explain the distinction between *geologic erosion* and *accelerated erosion.* Is the difference between the two greater in humid or arid regions?
2. When erosion takes place by wind or water, what are the three important types of damages that result on the land whose soils are eroding? What are the five important types of damages that erosion causes in locations away from the eroding site?
3. What is a common *T* value, and what is meant by this term? Explain why certain soils have been assigned a higher *T* value than other soils.
4. Describe the three main steps in the water erosion process.
5. Many people assume that the amount of soil eroded on the land in a watershed (*A* in the universal soil-loss equation) is the same as the amount of sediment carried away by the stream draining that watershed. What factor is missing that makes this assumption incorrect? Do you think that this means the USLE should be renamed?
6. Why is the total annual rainfall in an area *not* a very good guide to the amount of erosion that will take place on a particular type of bare soil?
7. Contrast the properties you would expect in a soil with either a very high *K* value or a very low *K* value.
8. How much soil is likely to be eroded from a Keene silt loam in central Ohio, on a 12% slope, 100 m long, if it is in dense permanent pasture and has no supporting physical conservation practices like terraces applied to the land? Use the information available in this chapter to calculate an answer.
9. What type of conservation tillage leaves the greatest amount of soil cover by crop residues? What are the advantages and disadvantages of this system?
10. Why are narrow strips of grass planted on the contour sometimes called a "living terrace"?
11. In most forests, which component of the ecosystem provides the primary protection against soil erosion by water, the *tree canopy*, *tree roots*, or *leaf litter?*
12. Certain soil properties generally make land susceptible to erosion by wind or erosion by water. List four properties that characterize soils highly susceptible to wind erosion. Indicate which two of these properties should also characterize soils highly susceptible to water erosion, and which two should not.
13. Which two factors in the wind erosion prediction equation (WEQ) can be affected by tillage? Explain.
14. Why might the approach to restoring land damaged by tillage erosion be quite different than that used to restore productivity to land damaged by water erosion? Explain.
15. Describe a soil in land capability Class IIw in comparison with one in Class IVe.
16. Why is it important that there be a close relationship between land in the CRP and that considered to be HEL?

[16] https://www.youtube.com/watch?v=9MRCltkSZbw—be sure to watch both parts 1 and 2.

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REFERENCES

Benik, S. R., B. N. Wilson, D. D. Biesboer, B. Hansen, and D. Stenlund. 2003. "Evaluation of erosion control products using natural rainfall events." *Journal of Soil and Water Conservation* **58**:98–104.

Carter, M. R. 1994. *Conservation Tillage in Temperate Agroecosystems*. Lewis Publishers, Boca Raton, FL.

Cassel, D. K., and R. Lal. 1992. "Soil physical properties of the tropics: Common beliefs and management constraints." In R. Lal and P. A. Sanchez (eds.). *Myths and Science of Soils of the Tropics.* SSA Special Publication No. 29. Soil Science Society of America, Madison, WI, pp. 61–89.

Chow, T. L., H. W. Rees, and J. L. Daigle. 1999. "Effectiveness of terraces/grassed waterway for soil and water conservation: A field evaluation." *Journal of Soil and Water Conservation* **54**:577–583.

Crovetto, C. 1996. *Stubble Over the Soil*. American Society of Agronomy, Madison, WI.

Daily, G. 1997. "Restoring value to the world's degraded lands." *Science* **269**:350–354.

de Jong, R., S. de Bruin, M. Schaepman, and D. Dent. 2011. "Quantitative mapping of global land degradation using earth observations." *International Journal of Remote Sensing* **32**:6823–6853.

Dickey, E. C., P. T. Jasa, B. J. Dolesh, L. A. Brown, and S. K. Rockwell. 1987. "Conservation tillage: Perceived and actual use." *Journal of Soil and Water Conservation* **42**:431–434.

Doolette, J. B., and J. W. Smyle. 1990. "Soil and moisture conservation technologies: Review of literature." In J. B. Doolette and W. B. Magrath (eds.). *Watershed Development in Asia: Strategies and Technologies*. World Book Technical Paper 127, Washington, D.C.

El-Swaify, S. A., and E. W. Dangler. 1982. "Rainfall erosion in the tropics: A state-of-the-art." *Soil Erosion and Conservation in the Tropics.* ASA Special Publication No. 43. American Society of Agronomy, Madison, WI.

FAO. 1987. *Protect and Produce*. U.N. Food and Agriculture Organization, Rome.

FAO. 2001. "The economics of conservation agriculture," FAO Y2781/E. Food and Agriculture Organization of the United Nations, Rome, p. 73. http://www.fao.org/docrep/004/Y2781E/y2781e00.htm#toc.

Flanagan, D. C., J. E. Gilley, and T. G. Franti. 2007. "Water erosion prediction project (WEPP): Development history, model capabilities, and future enhancements." *Transactions of the American Society of Agricultural and Biological Engineers* **50**:1603–1612.

Foster, G. R., and R. E. Highfill. 1983. "Effect of terraces on soil loss: USLEP factor values for terraces." *Journal of Soil and Water Conservation* **38**:48–51.

Friedrich, T., R. Derpsch, and A. Kassam. 2012. "Overview of the global spread of conservation agriculture." *The Journal of Field Actions* Special Issue 6.

Fryrear, D. W., and A. Saleh. 1993. "Field wind erosion: Vertical distribution." *Soil Science* **155**:294–300.

Fryrear, D. W., J. D. Bilbro, A. Saleh, H. Schomberg, J. E. Stout, and T. M. Zobeck. 2000. "RWEQ: Improved wind erosion technology." *Journal of Soil and Water Conservation* **55**:183–189.

Gao, X., Y. Xie, G. Liu, B. Liu, and X. Duan. 2015. "Effects of soil erosion on soybean yield as estimated by simulating gradually eroded soil profiles." *Soil and Tillage Research* **145**:126–134.

Gassman, P. W., A. M. Sadeghi, and R. Srinivasan. 2014. "Applications of the SWAT model special section: Overview and insights." *Journal of Environmental Quality* **43**:1–8.

Gilley, J. E., B. Eghball, L. A. Kramer, and T. B. Moorman. 2000. "Narrow grass hedge effects on runoff and soil loss." *Journal of Soil and Water Conservation* **55**:190–196.

Guo, Z., and M. Shao. 2013. "Impact of afforestation density on soil and water conservation of the semiarid loess plateau, China." *Journal of Soil and Water Conservation* **68**:401–410.

Hillel, D. 1991. *Out of the Earth: Civilization and the Life of the Soil*. The Free Press, New York.

Hockensmith, R. D., and J. G. Steele. 1949. "Recent trends in the use of the land-capability classification." *Soil Science Society of America Proceedings* **14**:383–388.

Hooke, R. L. 2000. "On the history of humans as geomorphic agents." *Geology* **28**:843–846.

Hosonuma, N., M. Herold, V. D. Sy, R. S. D. Fries, M. Brockhaus, L. Verchot, A. Angelsen, and E. Romijn. 2012. "An assessment of deforestation and forest degradation drivers in developing countries." *Environmental Research Letters* **7**:044009.

Klingberg, K., and C. Weisenbeck. 2011. "Shallow vertical tillage: Impact on soil disturbance and crop residue." *Proceedings of the 2011 Wisconsin Crop Management Conference* **50**:46–49. http://www.soils.wisc.edu/extension/wcmc/proc/2011_wcmc_proc.pdf#page=54.

Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012a. "Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio." *Soil Science Society of America Journal* **76**:1798–1809.

Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012b. "Long-term tillage and crop rotations for 47–49 years influences hydrological properties of two soils in Ohio." *Soil Science Society of America Journal* **76**:2195–2207.

Lambin, E. F., and P. Meyfroidt. 2011. "Global land use change, economic globalization, and the looming land scarcity." *Proceedings of the National Academy of Sciences* **108**:3465–3472.

Li, S., D. A. Lobb, R. G. Kachanoski, and B. G. McConkey. 2011. "Comparing the use of the traditional and repeated-sampling-approach of the ^{137}Cs technique in soil erosion estimation." *Geoderma* **160**:324–335.

FOR REFERENCE PURPOSES ONLY

Li, X. R., H. L. Xiao, M. Z. He, and J. G. Zhang. 2006. "Sand barriers of straw checkerboards for habitat restoration in extremely arid desert regions." *Ecological Engineering* **28**:149–157.

Lobb, D. 2008. "Soil movement by tillage and other agricultural activities." In S. E. J. a. B. D. Fath (ed.). *Encyclopedia of Ecology*. Elsevier, Oxford, pp. 3295–3303, Vol. 4.

Montgomery, D. R. 2007. "Soil erosion and agricultural sustainability." *Proceedings of the National Academy of Sciences* **104**:13268–13272.

Munson, S. M., J. Belnap, and G. S. Okin. 2011. "Responses of wind erosion to climate-induced vegetation changes on the Colorado plateau." *Proceedings of the National Academy of Sciences* **108**: 3854-3859.

Nyland, R. D. 1996. *Silviculture: Concepts and Applications*. McGraw-Hill, New York.

Oldeman, L. R. 1994. "The global extent of soil degradation." In D. J. Greenland and I. Szabolcs (eds.). *Soil Resilience and Sustainable Land Use*. CAB International, Wallingford, UK, pp. 99–118.

Oschwald, W. R., and J. C. Siemens. 1976. "Conservation tillage: A perspective," Agronomy Facts SM-30. University of Illinois, Urbana, IL.

Pierre, C. J. M. G. 1992. *Fertility of Soils: A Future for Farming in the West African Savannah*. Springer-Verlag, Berlin.

Pimentel D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. "Environmental and economic costs of soil erosion and conservation benefits." *Science* **267**:1117–1122.

Ramos, M. C., and J. A. Martinez-Casasnovas. 2006. "Nutrient losses by runoff in vineyards of the Mediterranean Alt Penedes region (ne Spain)." *Agriculture Ecosystems & Environment* **113**:356–363.

Renard, K. G., G. Foster, D. Yoder, and D. McCool. 1994. "RUSLE revisited: Status, questions, answers and the future." *Journal of Soil and Water Conservation* **49**:213–220.

Reusser, L., P. Bierman, and D. Rood. 2015. "Quantifying human impacts on rates of erosion and sediment transport at a landscape scale." *Geology.* doi: 10.1130/G36272.1XX:XX.

Schwab, G. O., D. D. Fangmeirer, and W. J. Elliot. 1996. *Soil and Water Management Systems*, 4th ed. Wiley, New York.

Schertz, D. L. 1983. "The basis for soil loss tolerance." *Journal of Soil and Water Conservation* **30**:10–14.

Shen, Z. Y., Y. W. Gong, Y. H. Li, Q. Hong, L. Xu, and R. M. Liu. 2009. "A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong watershed in the three gorges reservoir area." *Agricultural Water Management* **96**:1435–1442.

Sidle, R. C., A. D. Ziegler, J. N. Negishi, A. R. Nik, R. Siew, and F. Turkelboom. 2006. "Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia." *Forest Ecology and Management* **224**:199–225.

Stout, J. E., and J. A. Lee. 2003. "Indirect evidence of wind erosion trends on the southern high plains of North America." *Journal of Arid Environments* **55**:43–61.

Tatarko, J. 2010. "Wind erosion: Problem, processes, and control." USDA-Agricultural Research Service, Engineering and Wind Erosion Research Unit, Manhattan, KS. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_019407.pdf.

USDA. 1994. *Summary Report: 1992 National Resources Inventory*. USDA Natural Resources Conservation Service, Washington, D.C.

USDA. 1995. *Agricultural Handbook No. 703*. U.S. Department of Agriculture, Washington, D.C.

USDA/ARS. 2014. "The soil and water assessment tool (SWAT) [Online]." Available by USDA Agricultural Research Service and Texas A&M AgriLife Research (posted 30 September 2014).

USDA National Agricultural Statistics Service. 2014. *Census of Agriculture-2012*. Geographic Area Series AC-12-A-51. USDA, Washington, D.C. http://www.agcensus.usda.gov/Publications/2012/.

USDA-NRCS. 2006. "Annual national resources inventory for 2003: Soil erosion." U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/technical/land/nri03/SoilErosion-mrb.pdf (posted May 2006; verified 31 May 2006).

WHO. 2013. "Health effects of particulate matter." World Health Organization, Copenhagen, Denmark. http://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf.

Wilkinson, B. H., and B. J. McElroy. 2007. "The impact of humans on continental erosion and sedimentation." *Geological Society of America Bulletin* **119**:140–150.

Wischmeier, W. J., and D. D. Smith. 1978. *Predicting Rainfall Erosion Loss—A Guide to Conservation Planning.* Agricultural Handbook No. 537. USDA, Washington, D.C.

Zobeck, T. M., and R. S. Van Pelt. 2014. "Wind erosion." USDA Agricultural Research Service, Lincoln, NE. http://digitalcommons.unl.edu/usdaarsfacpub/1409/.

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Polluted soil at abandoned oil refinery. (Ray R. Weil)

18 Soils and Chemical Pollution

Black and portentous this humor prove, unless good counsel may the cause remove . . .
—*W. Shakespeare,* Romeo and Juliet

Every year, millions of tons of potentially toxic industrial, domestic, and agricultural products and waste materials find their way into the world's soils. Once there, they become part of biological cycles that affect all forms of life. In previous chapters we highlighted the enormous capacity of soils to accommodate added organic and inorganic chemicals. Tons of organic residues are broken down by soil microbes each year (Chapter 12), and large quantities of inorganic chemicals are fixed or bound tightly by soil minerals (Chapter 14). But we also learned of the limits of the soil's capacity to sorb these chemicals, and how environmental quality suffers when these limits are exceeded (Chapters 8 and 16).

We have seen some of the many ways in which soils and soil processes influence environmental quality. Soil processes affect the production and sequestering of greenhouse gases, such as nitrous oxide, methane, and carbon dioxide (see, e.g., Sections 12.9 and 13.8). Other nitrogen- and sulfur-containing gases come to earth in acid rain (see, e.g., Section 9.6). Mismanaged irrigation projects on arid-region soils result in the accumulation of salts (see Section 10.3), including toxic levels of sodium, selenium, and arsenic (Chapter 15).

We have also seen how fertilizer and manure applications that leave excess quantities of nutrients in the soil can result in the contamination of ground and surface waters with nitrates (Section 13.8) and phosphates (Section 14.2). The eutrophication of lakes, estuaries, and slow-moving rivers is evidence of these nutrient buildups. Huge "animal factories" for meat and poultry production produce mountains of manure that must be disposed of without loading the environment with unwanted chemicals, hormones and pathogens that are harmful to humans and other animals (Section 16.4).

In this chapter we will focus on potentially toxic chemicals that contaminate soils, threaten the health of organisms, and degrade soil quality. Some of the contaminants may escape the soil to extend their environmental damage to plants, animals, water, and air. In terms of their chemical nature, the toxic materials of concern can be viewed as being organic compounds, inorganic substances (mostly metallic elements), or radioactive isotopes, and we will consider them in that order. The brief review of soil pollution is intended as an introduction to the nature of major pollutants, their reactions in soils, and alternative means of managing, destroying, or inactivating them.

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18.1 TOXIC ORGANIC CHEMICALS

The quantity of synthetic organic chemicals manufactured every year is enormous—globally in 2012 more than 500 million Mg with a monetary value of some $5 trillion. Included are plastics and plasticizers, lubricants and refrigerants, fuels and solvents, pesticides and preservatives. Some are extremely toxic to humans and other life. Through accidental leakage and spills or through planned burial, spraying, or other treatments, synthetic organic chemicals can be found in virtually every corner of our environment—in the soil, in the groundwater, in the plants, in the ocean, and in our own bodies.

Environmental Damage from Organic Chemicals

These artificially synthesized compounds are termed **xenobiotics** because they are unfamiliar to the living world (Greek *xeno*, strange). Being nonnatural, many xenobiotics are either toxic to living organisms or resistant to biological decay, or both. The chemical structures of xenobiotic compounds may be quite similar to those of naturally occurring compounds produced by microorganisms and plants. The difference is commonly the insertion of halogen atoms (Cl, F, Br) or multivalent nonmetal atoms (such as S and N) into the structure (see Figure 18.1).

Some xenobiotic compounds are relatively inert and harmless, but others are biologically damaging even in very small concentrations. Those that find their way into soils may inhibit or kill soil organisms, thereby undermining the balance of the soil community (see Section 11.14). Other chemicals may be transported from the soil to the air, water, or vegetation, where they may be contacted, inhaled, or ingested by any number of organisms, including people. It is imperative, therefore, that we control the release of organic chemicals and that we learn of their fate and effects once they enter the soil.

Organic chemicals may enter the soil as contaminants in industrial and municipal organic wastes applied to or spilled on soils, as components of discarded machinery, in large or small lubricant and fuel leaks, as military explosives, as deposition from the atmosphere, or as sprays applied to control pests in terrestrial ecosystems. Pesticides are probably the most widespread organic pollutants associated with soils. In the United States, pesticides are used on some 150 million ha of land, three-fourths of which is agricultural land. Soil contamination by other organic chemicals tends to be much more localized. We will therefore emphasize the pesticide problem.

The Nature of the Pesticide Problem[1]

Pesticides are chemicals that are designed to kill pests (i.e., any organism unwanted by the pesticide user). Some 700 chemicals in about 50,000 formulations are used to control various pests in all parts of the world. Globally, about 3 billion kg of pesticides costing about $60 billion are applied each year. Some 500,000 Mg of organic pesticide chemicals are used annually in the United States, alone.

Statistics on the amounts of pesticides used can be difficult to interpret. Figure 18.2 (*left*) presents trends in agricultural pesticide use in the United States across five decades. Back in 1960 when Rachel Carson wrote her famous book, *Silent Spring*, most of the pesticide materials used were highly toxic insecticides, such as DDT. During the subsequent 20 years overall pesticide use rose rapidly due mainly to the advent of chemical herbicides effective at selectively killing unwanted plants (weeds). By the 1990s, insecticides accounted for a much smaller fraction of pesticide use. Herbicide use (mainly glyphosate) increased again after 2000 with the wide adoption of corn and soybean cultivars genetically engineered to resist that broad spectrum herbicide. The total amount of insecticide used declined steadily during the entire period, mainly because of the introduction of more potent compounds requiring lower application rates and, in the late 1990s, the introduction of crops genetically engineered to produce their own insecticidal toxins (derived from the soil bacterium, *Bacillus thuringiensis*, or Bt).

[1]Rachel Carsen's groundbreaking warning (Carson, 1962) about the ecological dangers of excessive pesticide use is still very worth reading today, as is Miguel Altieri's classic text (Altieri, 1995) on pesticide-free farming and agro-ecology. For research on glyphosate residues in genetically modified soybeans and their potential effects on animal health, see Bøhn et al. (2014) and Cuhra et al. (2015).

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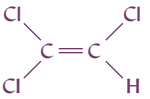
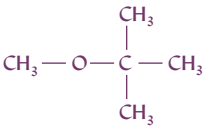
Industrial Xenobiotics

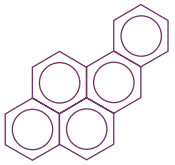
(a PCB)
4′,4′-Dichlorbiphenyl



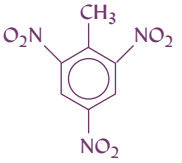
(TCE)
Trichloroethylene



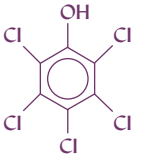
(MTBE)
Methyl tertiary butyl ether



(PAH)
Polycyclic aromatic hydrocarbon

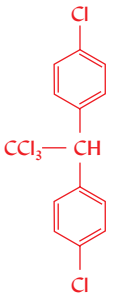


(TNT)
2,4,6-Trinitrotoluene

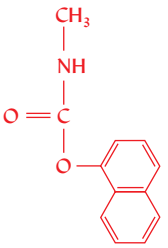


(PCP)
Pentachlorophenol

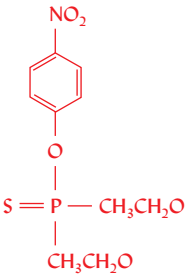
Insecticides



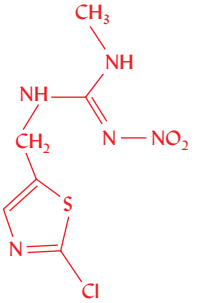
(DDT)
Chlorinated hydrocarbons



(Carbaryl)
Carbamates

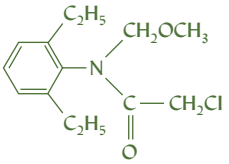


(Parathion)
Organophosphates

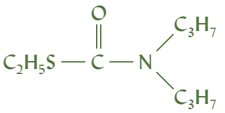


(Clothianidin)
Neonicotinoids

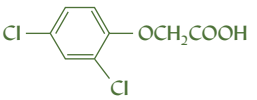
Herbicides



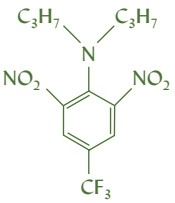
(Alachlor)
Acetanilides



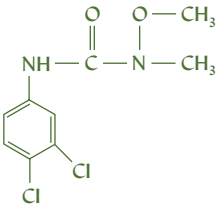
(EPTC)
Carbamothioates



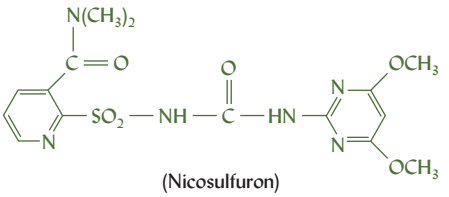
(2,4–D)
Phenoxyalkanoic acids



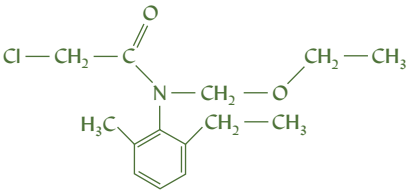
(Trifluralin)
Dinitroanilines



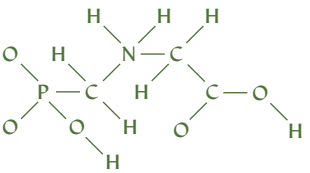
(Linuron)
Substituted ureas



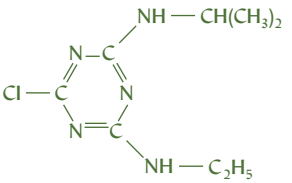
(Nicosulfuron)
Sulfonylureas



Acetochlor



Glyphosate



(Atrazine)
Triazines

Figure 18.1 *Structural formulae of representative compounds in 18 classes of widespread organic contaminants. Carbaryl, DDT, parathion, and clothianidin are insecticides; the lower nine compounds shown are herbicides. The widely differing structures result in a great variety of toxicological properties and reactions in the soil.*

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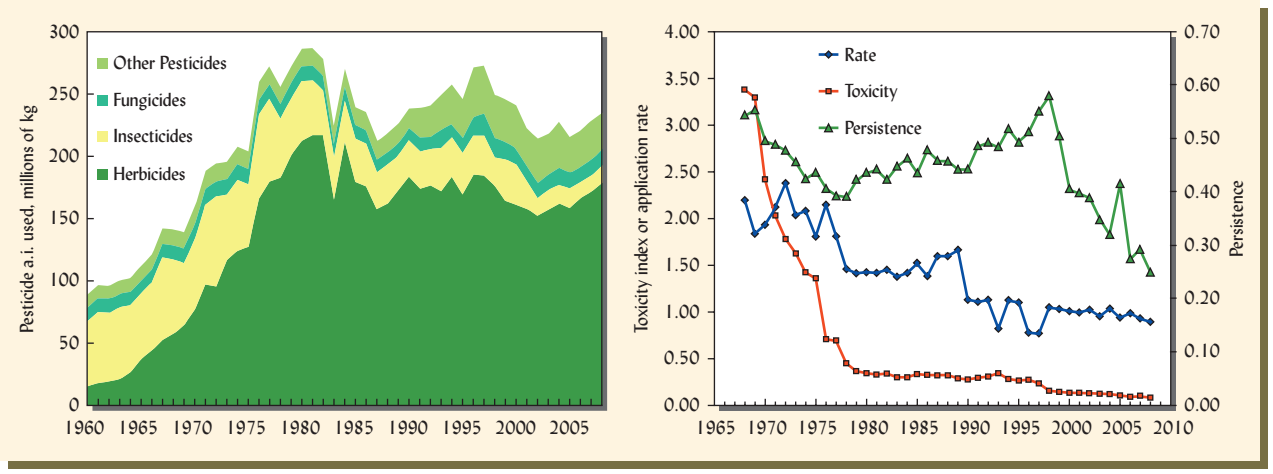

Figure 18.2 *Types, amounts, and nature of pesticides used on 21 major crops in the United States across five decades.* (Left) *The total amount of pesticides used (kg of active ingredient, a.i.) increased dramatically between 1960 and 1980, mainly due to greater amounts of herbicides used. With adoption of herbicide resistant corn and soybean, herbicide use (mainly glyphosate) increased again after 2000. Insecticide use decreased steadily during the entire period, mainly because of the use of more potent compounds requiring lower rates and the introduction in the late 1990s of crops genetically engineered to produce their own insecticidal Bt toxins. In addition to herbicides, insecticides, and fungicides, "other pesticides" included soil fumigants, desiccants, harvest aids, and plant growth regulators.* (Right) *The index of chronic toxicity (1/threshold μg L^{-1}) of pesticides used declined dramatically during the 1970s when DDT and aldrin were phased out, and has continued to decline slowly since 1980. The pesticides in use in 2010 were far less toxic than those used several decades earlier. The persistence index (the fraction of compounds in use that have half-lives >60 days) declined somewhat.* [Graphed from data in Fernandez-Cornejo et al. (2014)]

Although the total amount of pesticides used in the United States may have dropped somewhat since the 1980s, formulations of both insecticides and herbicides in use today are generally more potent, so that smaller quantities need be applied per hectare to achieve toxicity to the pest. In general, the toxicity to humans and wildlife of the newer pesticides is thought to be much lower than that of those in use prior to the 1980s (Figure 18.2, *right*). However, there is concern that some of the newer, ostensibly safer compounds may have more subtle, long-term effect on humans and wildlife such as endocrine (hormone) disruption. In addition, newer pesticide compounds may be more or less persistent in the environment than the compounds they supplanted.

Benefits of Pesticides. Pesticides have provided many benefits to society. They have helped control mosquitoes and other vectors of such human diseases as malaria, yellow fever and West Nile virus. Bed nets treated with long-lasting insecticides have recently helped turn the tide against the ravages of malaria in many tropical countries. Similar insecticides are essential in stopping the spread of bedbugs that are resurgent in many industrial countries, especially in hotels. They have protected crops and livestock against insects and diseases that could devastate food production. Without the control of weeds by chemicals called *herbicides*, conservation tillage (especially no-tillage) would be much more difficult to adopt. Without herbicides farmers would have to rely mainly on tillage to manage weeds and much of the progress made in controlling soil erosion probably would not have come about (Section 17.6). Also, pesticides reduce the spoilage of food as it moves from farm fields to distant dinner tables. In addition, long-lasting insecticides applied to soils around our houses prevent costly damages from wood eating soil-dwelling termites (Section 11.5).

Problems with Pesticides. While the benefits to society from pesticides must be acknowledged, so too must the costs (Table 18.1). Widespread and heavy use of pesticides on agricultural soils and suburban and urban landscapes has led to contamination of both surface and groundwater (Table 18.2). Therefore, when pesticides are used, they should be chosen for low toxicity to humans and wildlife, low mobility on soils, and low persistence (see Section 18.3). Even then, the use of pesticides often has wide-ranging detrimental effects on soil and aquatic

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Table 18.1
TOTAL ESTIMATED ENVIRONMENTAL AND SOCIAL COSTS FROM PESTICIDE USE IN THE UNITED STATES

Type of impacts[a]	Annual costs Millions of $
Public health impacts	1,596
Domestic animals deaths and contaminations	42
Loss of natural enemies	728
Cost of pesticide resistance	2,100
Honeybee and pollination losses	467.6
Crop losses	1,947.4
Fishery losses	140
Bird losses	3,024
Groundwater contamination	2,800
Government regulations to prevent damage	658
Total	13,503

[a]The death of an estimated 60 million wild birds may represent an additional substantial cost in lost revenues from hunters and bird watchers.
Data adjusted for inflation to 2015 dollars and other changes, selected from Pimentel and Burgess (2014).

microbial and faunal communities. In fact, the harm done, though not always obvious, may outweigh the benefits. Examples include insecticides that kill natural enemies of pest species as well as the target pest (sometimes creating new major pests from species formerly controlled by natural enemies) and fungicides that kill both disease-causing and beneficial mycorrhizal fungi (see Section 11.9). Given these facts, it should not come as a surprise that despite the widespread use of pesticides, insects, diseases, and weeds still cause the loss of about one-third of today's crop production, about the same proportion of crops lost to these pests in the United States before synthetic organic pesticides were in use. Still, most economic analysis show that even when environmental and social impacts included on the costs side, the use of pesticides brings a net benefit to the United States and probably to many other countries where they are similarly used.

Alternatives to Pesticides. Pesticides should not be seen as a panacea, or even as indispensable. Some farmers, most notably the small but increasing number who practice **organic farming**,[2] produce profitable, high-quality yields without the use of synthetic pesticides. In any case, chemical pesticides should be used as a *last* resort, rather than as a *first* resort, for pest management, whether on a farm, an ornamental landscape, a forest, an urban neighborhood, or in a building. Before using toxic insecticides or herbicides, every effort should be made to minimize the detrimental effects of pests by managing the environment to increase biodiversity, favor natural enemies of pests, and change aspects of the environment that encourage pest outbreaks or allow pests to cause damage. Such nonchemical management requires detailed knowledge of the pest's life cycle with a view to taking advantage of its particular weaknesses.

For example, instead of insecticide spraying to kill mosquitoes in an urban neighborhood, a campaign could be established to search out and remove all containers (old tires, jars, dog dishes, etc.) that can hold 2 cm of rainwater for two days—habitat elements in which the mosquitoes can breed. The tools employed in agricultural fields may include crop diversification, establishment of habitat for beneficial insects that prey upon the pest, application of organic soil amendments to stimulate acquired immune responses, implementation of cultural practices such as planting dates, rates, patterns, and intercrops that reduce the ability of weed

[2]The term *organic farming* has little to do with the chemical definition of organic, which simply indicates that a compound contains carbon. Rather, it refers to a system and philosophy of farming that eschews the use of synthetic chemicals while it emphasizes soil organic matter and biological interactions to manage agroecosystems. See Section 20.9.

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Table 18.2
PROPERTIES OF SELECTED PESTICIDES COMMONLY FOUND IN WATER
The distribution coefficients for organic carbon (K_{oc}), solubilities in water (S_w), and half-lives help determine how easily compounds move to ground and surface water. Detections, maximum concentrations observed, and health advisory levels should be compared to suggest the seriousness of groundwater contamination.

Pesticide compound	log K_{oc} (mL/g)	S_w (mg/L)	Half-life for transformation in aerobic soil (days)	Half-life for transformation in water (days)	Maximum concentration observed (μg/L)	Health criterion (μg/L)
Agricultural herbicides and degradates frequently detected in water						
Atrazine	2.00	30	146	742	3.8	3[a]
Desethylatrazine	1.90	2700	170	NA	2.6	—
Metolachlor	2.26	430	26	410	5.4	100[b]
Alachlor	2.23	240	20.4	640	0.55	2[a]
Acetochlor	2.38	223	14	2300	—	—
Metribuzin	1.72	1000	172	>200	0.30	200[b]
EPTC	2.30	370	7	>200	0.45	—
Trifluralin	4.14	0.5	169	>32	0.014	5[b]
Urban herbicides and degradates frequently detected in water						
Simazine	2.11	5	91	>32	1.3	4[a]
2,4-D	1.68	890	2.3	732	—	70[a]
Diuron	2.60	40	372	>500	—	10[b]
Bromacil	1.86	815	275	>30	—	90[b]
Insecticides frequently detected in water						
Diazinon	2.76	60	39	140	0.077	0.6[b]
Chlorpyrifos	3.78	0.73	30.5	29	0.005	20[a]
Carbofuran	2.02	351	11	289	1.3	40[a]
Carbaryl	2.36	120	17	11	0.02	700[b]
Malathion	3.26	145	<1	6.3	0.004	100[b]
Dieldrin	4.08	0.17	NA	3830	0.45	0.002[c]
Imidacloprid	2.2	54	200	30	10.0	0.013[a]

Data from several sources: Gilliom et al. (2006), Vijver and van den Brink (2014).
[a]Maximum contaminate level (MCL) permissible as an annual average concentration in public-use water.
[b]Health advisory level (HA-L), the concentration expected to cause health problems (noncancer) with lifetime exposure.
[c]Cancer risk concentration (CRC).

to compete, and the selection of pest-resistant plant cultivars. Too often, because pesticides are available as a convenient crutch, these more sophisticated ecological approaches to pest management are not thoroughly explored.

Nontarget Damages. Although some pesticides are intentionally applied to soils, most reach the soil inadvertently. When pesticides are sprayed in the field, most of the chemical misses the target organism. For pesticides aerially applied to forests, about 25% reaches the tree foliage, and far less than 1% reaches a target insect. About 30% may reach the soil, while about half of the chemical applied is likely to be lost into the atmosphere or in runoff water.

Designed to kill living things, many of these chemicals are potentially toxic to organisms other than the pests for which they are intended. Some are detrimental to nontarget organisms

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related to the target pests, such as beneficial insects and certain soil organisms. Those chemicals that do not quickly break down may be biologically magnified as they move up the food chain. For example, as earthworms ingest contaminated soil, the chemicals tend to concentrate in the fatty tissues of the earthworm bodies. When birds, moles, or fish eat the earthworms, the pesticides can build up further to lethal levels. The near extinction of certain birds of prey (including the American bald eagle) during the 1960s and 1970s called public attention to the sometimes-devastating environmental consequences of pesticide use. More recently, evidence is mounting to suggest that endocrine (hormone) balance in humans and other animals may be disrupted by the minute traces of some pesticides found in water, air, and food.

18.2 KINDS OF ORGANIC CONTAMINANTS

Industrial Organics

Industrial organics that often end up contaminating soils by accident or neglect include petroleum products used for fuel [gasoline components such as benzene, and more complex polycyclic aromatic hydrocarbons (PAHs)], solvents used in manufacturing processes [such as trichloroethylene (TCE)], and military explosives such as trinitrotoluene (TNT). Several examples of their structures are shown in Figure 18.1. Polychlorinated biphenyls (PCBs) constitute a particularly troublesome class of widely dispersed compounds. These compounds can disrupt reproduction in birds and cause cancer and hormone effects in humans and other animals. Several hundred varieties of liquid or resinous PCBs were produced from 1930 to 1980 and used as specialized lubricants, hydraulic fluids, and electrical transformer insulators, as well as in certain epoxy paints and many other industrial and commercial applications. Because of their extreme resistance to natural decay and their ability to enter food chains, even today soil and water all over the globe contain at least traces of PCBs.

The sites most intensely contaminated with organic pollutants are usually located near chemical manufacturing plants or oil storage facilities, but railway, shipping, and highway accidents also produce hot spots of contamination. Thousands of neighborhood gas stations represent potential or actual sites of soil and groundwater contamination as gasoline leaks from old, rusting underground storage tanks (Figure 18.3). However, as already mentioned, by far the most widely dispersed xenobiotics are those designed to kill unwanted organisms (i.e., pesticides).

Pesticides

Pesticides are commonly classified according to the type of pest organisms targeted: (1) *insecticides*, (2) *fungicides*, (3) *herbicides* (weed killers), (4) *rodenticides*, and (5) *nematocides.* In practice, all find their way into soils and from there into streams (Figure 18.4). Since the first three are used in the largest quantities and are therefore more likely to contaminate soils, they will be given primary

Figure 18.3 *Leaking underground storage tank (LUST) replacement at a gas station in California, USA. The old rusting steel tanks have been removed and replaced by more corrosion-resistant fiberglass tanks, which are set in the ground and covered with pea gravel. The soil and groundwater aquifer beneath the tanks were cleaned up using special techniques to stimulate soil microorganisms and to pump out volatile organics such as benzene vapors. Remediation and replacement can cost about $1 million for a single large gas station.* (Photo courtesy of Ray R. Weil)

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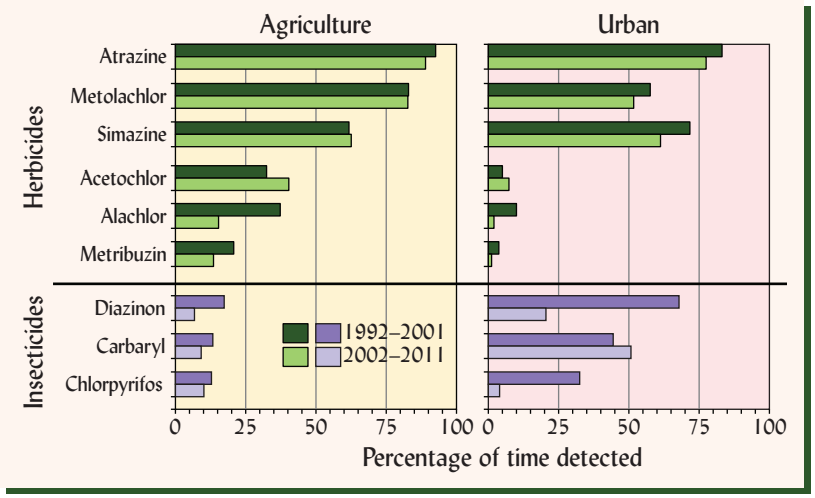

Figure 18.4 *Percentage of streams samples in the United States in which selected pesticides were detected during two time periods in relation to land-use in the watersheds. In watershed classed* Agriculture *greater than 50% of the land was in agricultural use and less than 10% was urban. In watersheds classed* Urban *more than 25% of the land was urban and less than 25% was in agricultural use. Across all land-use classifications, the herbicides atrazine, metolachlor, and simazine were detected in more than 50% of the streams samples. Insecticides tended to be detected more frequently in urban than in agricultural watersheds. The potential for adverse effects on aquatic life is likely greater than these results indicate because potentially important pesticide compounds were not included in the assessment. Human-health benchmarks were much less frequently exceeded, and during 2002–2011, only one agricultural stream and no urban or mixed-land-use streams exceeded human-health benchmarks for any of the measured pesticides.* [Modified from Stone et al. (2014)]

consideration. Figure 18.1 shows that most pesticides contain aromatic rings of some kind, but that there is great variability in pesticide chemical structures.

Insecticides. Most of these chemicals are included in four general groups. The *chlorinated hydrocarbons,* such as DDT, were the most extensively used until the early 1970s, when their use was banned or severely restricted in many countries due to their low biodegradability and persistence, as well as their toxicity to birds and fish. The *organophosphate* pesticides are generally biodegradable, and thus less likely to build up in soils and water. However, they are extremely toxic to humans, so great care must be used in handling and applying them. The *carbamates* are considered least dangerous because of their ready biodegradability and relatively low mammalian toxicity. However, they are highly toxic to honeybees and other beneficial insects and to earthworms. The *neonicotinoids* are a relatively new class of insecticides with chemical structures similar to that of nicotine (the toxic and addictive ingredient in tobacco). They affect the central nervous system of insects. Neonicotinoids exhibit chronic toxicity to aquatic organisms at very low concentrations; for example, imidacloprid is toxic in the range of 10–100 *nano*grams (ng) per L. Minute quantities of neonicotinoids have been found to kill brain cells in bees, causing these critical pollinators to lose their ability to navigate between their nests and flowers.

Neonicotinoid insecticides are highly soluble in water and somewhat slow to degrade in the environment, therefore they easily move off the land into surface water and groundwater. This highly soluble insecticide also is subject to being carried by runoff and leaching water to nearby streams (Figure 18.5). Research suggests that dust from planting seeds coated with

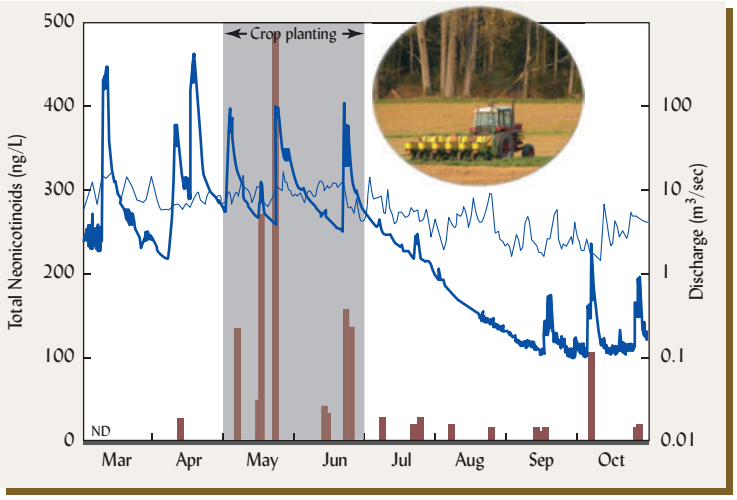

Figure 18.5 *Total neonicotinoid concentrations detected (bars) in a stream draining an area of intense corn and soybean production in the Midwestern United States. Stream discharge (flow) during the sampling year (dark blue line) and average discharge are shown to highlight the wet spring and dry summer of the sampling year compared to an average year. The timing of corn and soybean planting is shown by the shaded rectangle. Temporal patterns in concentrations reveal pulses of neonicotinoids associated with rainfall events during crop planting, suggesting seed treatments as their likely source. Some studies suggest that the threshold level of neonicotinoids that can cause acute toxicity to aquatic organisms are as low as 200 ng/L and for chronic toxicity as low as 20 ng/L.* [Modified from USGS data in Hladik et al. (2014)]

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neonicotinoids may be partially responsible for drastic declines in honeybees and other pollinator insects. While the use of organophosphate and carbamate insecticides on crops in the United States has declined during the past two decades, the use of neonicotinoid insecticides has increased dramatically, mainly in seed coatings.

Fungicides. Fungicides are used mainly to control diseases of fruit and vegetable crops and as seed coatings to protect against seed rots. Some are also used to protect harvested fruits and vegetables from decay, to prevent wood decay, and to protect clothing from mildew. Organic materials such as the thiocarbamates and triazoles are currently in use.

Herbicides. The quantity of herbicides used in the United States exceeds that of the other types of pesticides combined. Starting with 2,4-D (a chlorinated phenoxyalkanoic acid), dozens of chemicals in literally hundreds of formulations have been placed on the market (see Figure 18.1). These include the *triazines*, used mainly for weed control in corn; *substituted ureas*; some *carbamates*; the relatively new *sulfonylureas*, which are potent at very low rates; *dinitroanilines*; and *acetanilides*, which have proved to be quite mobile in the environment. One of the most widely used herbicides, *glyphosate* (e.g., Roundup®), does not belong to any of the aforementioned chemical groups. Unlike most herbicides, it is nonselective, meaning that it will kill almost any plant, including crops. However, a gene that confers resistance to its effects has been discovered and engineered into several major crops. These genetically engineered crops can then be grown with a very simple, convenient method of weed control that usually consists of one or two sprayings of glyphosate that will kill all plants other than the resistant crop. As might be expected from the interaction of human nature (overdoing a convenient thing) with Mother Nature (evolution to select the fittest), the overuse of glyphosate in this system has lead to an increasing number of important weed species developing resistance to this herbicide. Its overuse has also lead to the detection of potentially chronically toxic levels of glyphosate and its breakdown products in soybeans destined for human and animal foods (see footnote 1).

The wide variation in herbicide chemical makeup provides an equally wide variation in properties. Most herbicides are biodegradable, and most of them are relatively low in mammalian toxicity. However, some are quite toxic to fish, soil fauna, and perhaps to other wildlife. They can also have deleterious effects on beneficial aquatic vegetation that provides food and habitat for fish and shellfish. As for any chemicals, our knowledge about subtle chronic toxic effect of herbicides such as developmental changes, birth defects, performance changes, and degenerative diseases is much more uncertain than our knowledge of acute immediate poisoning.

Nematocides. Although nematocides are not as widely used as herbicides and insecticides, some of them are known to contaminate soils and the water draining from treated soils. For example, some carbamate nematocides dissolve readily in water, are not adsorbed onto soil surfaces, and consequently easily leach downward and into the groundwater. Other nematicidal chemicals are volatile soil fumigants that kill virtually all life in the soil, both the helpful and the harmful (Section 18.4). Methyl bromide, once the most commonly used of these fumigants, has been banned because of its adverse effects on the atmosphere and parts of the environment. Happily, the search for substitutes has led to the development of many nonchemical means to manage the pests once controlled by this highly toxic chemical (e.g., see Figure 11.23).

18.3 BEHAVIOR OF ORGANIC CHEMICALS IN SOIL[3]

Once they reach the soil, organic chemicals, such as pesticides or hydrocarbons, can follow one or more of eight pathways (Figure 18.6). They may: (1) vaporize into the atmosphere without chemical change; (2) they may be absorbed by clay or organic matter in soils; (3) move downward through the soil in liquid or solution form and be lost from the soil by leaching; (4) undergo chemical reactions within or on the surface of the soil; (5) decompose aerobically by the action of microorganisms in the aerated upper soil horizons; (6) decompose anaerobically by

[3]For reviews on organic chemicals in the soil environment, see Barth et al. (2009) and Pierzynski et al. (2004).

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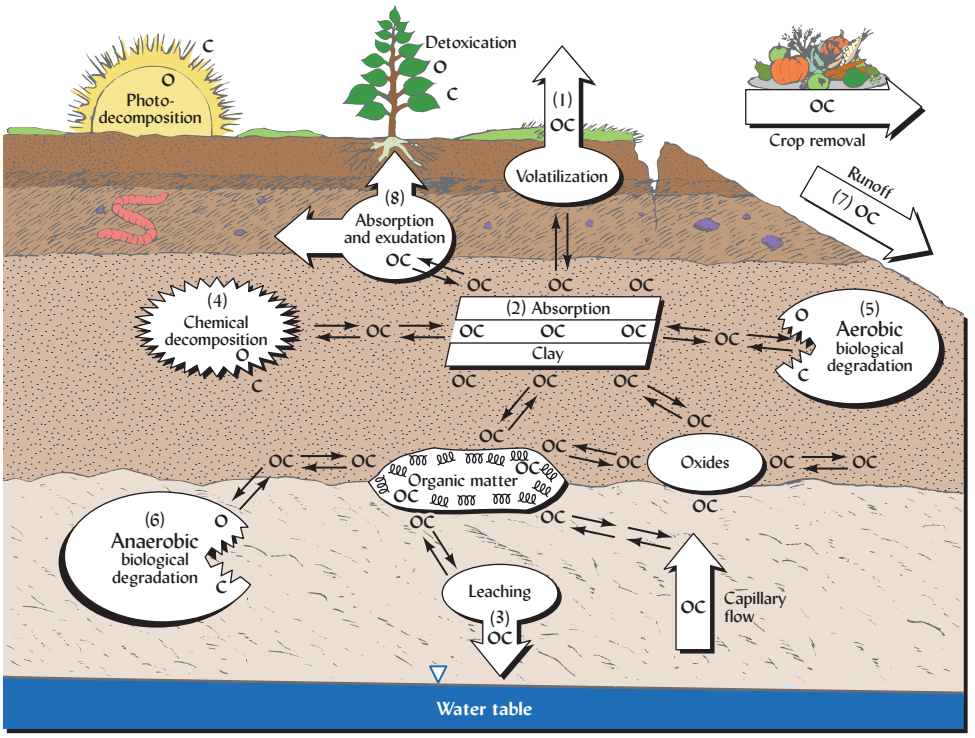

Figure 18.6 *Eight important processes affecting the dissipation of organic chemicals (OC) in soils. Note that the OC symbol is split up by decomposition (both by light and chemical reaction) and degradation by microorganisms, indicating that these processes alter or destroy the organic chemical. In transfer processes, the OC remains intact.* [Modified from Weber and Miller (1989)]

the action of microorganisms in hydric soils, saturated subsoils or groundwater; (7) wash into streams and rivers in surface runoff; and (8) move by uptake into plants or soil animals to be metabolized or passed up the food chain. The specific environmental fate of each chemical will be determined at least in part by its particular chemical structure and properties.

Volatility

Organic chemicals vary greatly in their volatility and subsequent susceptibility to atmospheric loss. Some soil fumigants, such as methyl bromide (now banned from most uses), were selected because of their very high vapor pressure, which permits them to penetrate soil pores to contact the target organisms. This same characteristic encourages rapid loss to the atmosphere after treatment, unless the soil is covered or sealed. A few herbicides (e.g., trifluralin) and fungicides (e.g., PCNB) are sufficiently volatile to make vaporization a primary means of their loss from soil. The lighter fractions of crude oil (e.g., gasoline and diesel) and many solvents vaporize to a large degree when spilled on the soil.

One cannot assume that disappearance of a pesticide from the soil is evidence of its breakdown into harmless products. Some chemicals lost to the atmosphere are known to return to the soil or to surface waters with the rain.

Adsorption

The degree to which an organic compound will be immobilized by adsorption to soil particles is determined largely by characteristics of both the chemical and the soil. Soil organic matter and high-surface-area clays tend to be the strongest adsorbents for some compounds (Figure 18.7), while oxide coatings on soil particles strongly adsorb others. The presence of certain functional groups, such as —OH, —NH_2, —NHR, —$CONH_2$, —COOR, and —$^+NR_3$, in the chemical structure encourages adsorption, especially on the soil humus. Hydrogen bonding (see Sections 5.1 and 8.3) and protonation [adding of H^+ to a group such as an —NH_2 (amino) group] probably promote adsorption. Everything else being equal, larger organic molecules with many charged sites adsorb more strongly.

Some organic chemicals with positively charged groups, such as the herbicides diquat and paraquat, are strongly adsorbed by silicate clays. Adsorption of certain pesticides molecules to clay particles tends to be greatest at low pH, which encourages *protonation* (Figure 18.8).

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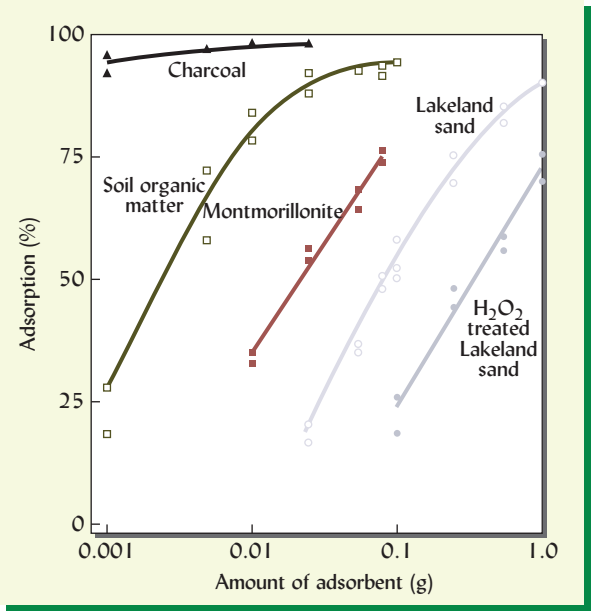

Figure 18.7 *Adsorption of polychlorinated biphenyl (PCB) by different soil materials. The Lakeland sand (Typic Quartzipsamments) lost much of its adsorption capacity when treated with hydrogen peroxide H_2O_2 to remove its organic matter. The amount of soil material required to adsorb 50% of the PCB was approximately ten times as great for montmorillonite (a 2:1 clay mineral) as for soil organic matter, and ten times again as great for H_2O_2 treated Lakeland sand. Later tests showed that once the PCB was adsorbed, it was no longer available for uptake by plants. Note that the amount of soil material added is shown on a log scale.* [From Strek and Weber (1982)]

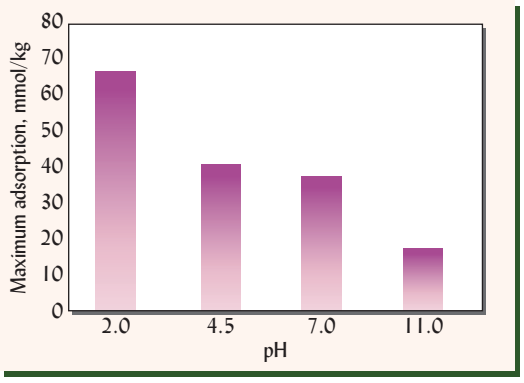

Figure 18.8 The maximum adsorption of glyphosate molecules onto kaolinite clay is reduced as the pH of the clay suspension is increased. [Graphed from tabular data in McConnell and Hossner (1985)]

Protonation, or the addition of H^+ ions to functional groups (e.g., —NH_2), yields a positive charge on the herbicide molecule, resulting in greater attraction to negatively charged soil colloids. The clay colloids in soils can thus strongly adsorb both positively charged organic compounds and other contaminants such as heavy metals (Section 18.8). On the other hand, the swarm of cations (Ca^{2+}, K^+, etc.) typically adsorbed on clay particle surfaces also make these surfaces hydrophilic and, as such, they are generally coated with adsorbed water. The hydrophilic nature of the clays greatly reduces their ability to adsorb many organic molecules which are hydrophobic in nature and without positively charged sites.

Leaching and Runoff

The tendency of organic chemicals to leach from soils is closely related to their solubility in water and their potential for adsorption. Some compounds, such as chloroform and phenoxyacetic acid, are a million times more water soluble than others, such as DDT and PCBs, which are quite soluble in oil but not in water. High water solubility favors leaching losses.

Strongly adsorbed molecules are not likely to move down the profile (Table 18.3). Likewise, conditions that encourage such adsorption will discourage leaching. Leaching is apt to be favored by water movement, the greatest leaching hazard occurring in highly permeable, sandy soils that are also low in organic matter. Periods of high rainfall around the time of application of the chemical promote both leaching and runoff losses (Table 18.4). With some notable exceptions (e.g., paraquat and glyphosate), herbicides seem to be somewhat more mobile than most fungicides or insecticides, and therefore are more likely to find their way to groundwater supplies and streams (Figure 18.9).

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Table 18.3
THE DEGREE OF ADSORPTION OF SELECTED HERBICIDES
Weakly adsorbed herbicides move more readily through the soil than those more tightly adsorbed.

Common name	Example trade name	Adsorptivity to soil colloids
Dalapon	Dowpon	None
Chloramben	Amiben	Weak
Bentazon	Basagran	Weak
2,4-D	Several	Moderate
Propachlor	Ramrod	Moderate
Atrazine	AAtrex	Strong
Alachlor	Lasso	Strong
EPTC	Eptam	Strong
Diuron	Karmex	Strong
Glyphosate	Roundup	Very strong
Paraquat	Paraquat	Very strong
Trifluralin	Treflan	Very strong
DCPA	Dacthal	Very strong

Table 18.4
SURFACE RUNOFF AND LEACHING LOSSES (THROUGH DRAIN TILES) OF THE HERBICIDE ATRAZINE FROM A CLAY LOAM LACUSTRINE SOIL (ALFISOLS) IN ONTARIO, CANADA
The herbicide was applied at 1700 g/ha in late May. The data are the average of three tillage methods. Note that the rainfall for May and June is related to the amount of herbicide lost by both pathways.

Year of study	Surface runoff loss	Drainage water loss	Total dissolved loss	Percent of total applied, %	Rainfall, May–June, mm
	Atrazine loss, g/ha				
1	18	9	27	1.6	170
2	1	2	3	0.2	30
3	51	61	113	6.6	255
4	13	32	45	2.6	165

Data abstracted from Gaynor et al. (1995).

Contamination of Groundwater

Experts once maintained that contamination of groundwater by pesticides occurred only from misuse or accidents such as spills, but it is now known that many pesticides reach the groundwater from normal agricultural use. Since many people (e.g., 40% of Americans) depend on groundwater for their drinking supply, leaching of pesticides is of wide concern. Table 18.2 lists some of the pesticides commonly found well water in the United States. The concentrations are given in μg/L or parts per billion (see Box 18.1). In some cases, the amount of pesticide found in the drinking water has been high enough to raise long-term health concerns (e.g., atrazine and dieldrin exceed the health safety criteria in Table 18.2).

Chemical Reactions

Upon contacting the soil, some pesticides undergo chemical modification independent of soil organisms. For example, insecticides of the neonicotinoid class decompose within hours or

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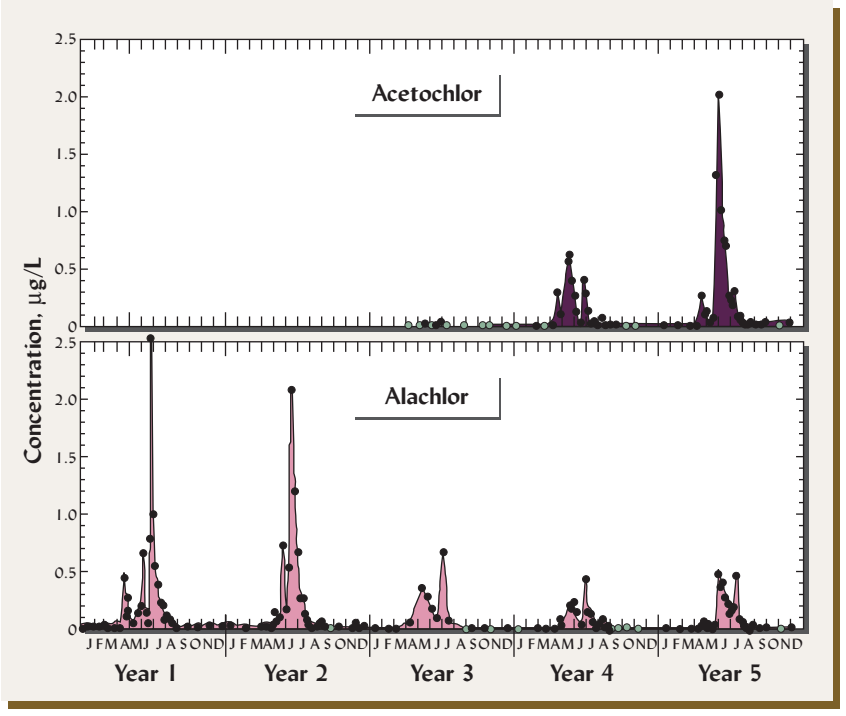

Figure 18.9 *Herbicides in the main U.S. corn-growing region illustrate the direct and rapid connection between the use of a chemical on the land and its concentration in streams and rivers. The White River near Hazelton, Indiana, was monitored over a five-year period. Note that the concentrations of the herbicide alachlor peaked every year in June, about a month after most farmers in the watershed sprayed their corn and soybean fields. In year 3, a new compound, acetochlor, partially replaced the older herbicide alachlor. Within a year of the introduction of the newer compound, acetochlor concentrations increased while alachlor concentrations decreased.* [From Gilliom et al. (2006)]

days if exposed to bright sunlight. In contrast, DDT, diquat, and the triazines are subject to slow photodecomposition in sunlight. The triazine herbicides (e.g., atrazine) and organophosphate insecticides (e.g., malathion) are subject to hydrolysis and subsequent degradation. While the complexities of molecular structure of the pesticides suggest different mechanisms of breakdown, it is important to realize that degradation independent of soil organisms does in fact occur.

Microbial Metabolism

Biochemical degradation by soil organisms is the single most important method by which pesticides are removed from soils. Some microbes may metabolize a pesticide or other organic xenobiotic compound as a food source, thus deriving energy and cellular constituents from the compound. In other cases, when the xenobiotic compound is not used as food by the organism, the enzymatic breakdown of the compound is termed cometabolism. In some cases, microorganism can mineralize xenobiotics all the way to simple CO_2 (or CH_4) and H_2O, but in other cases more complex and possibly toxic intermediary breakdown products accumulate.

The biochemical reactions occurring in aerated environments are quite different from those in anaerobic environments. Many organic xenobiotics contain one or more aromatic carbon rings on which halides (Cl, F, Br) or NH_2 or NO_3 groups are attached (Figure 18.1). The first steps in degradation usually involve the removal of these attached groups, after which the rings themselves can be cleaved (opened up). Certain soil fungi (Basidiomycetes or "white rot fungi") are especially important in the breakdown of certain recalcitrant xenobiotics that can be degraded by the same enzymes that these fungi use to metabolize natural polymers like lignin. In aerobic environments, certain polar groups on the pesticide molecules, such as —OH, —COO^-, and —NH_2, can provide points of attack for the organisms' enzymes, but the presence of halogens may prevent this enzymatic action. For most aerobic microorganisms the oxidative removal of halogens (dehalogenation) and addition of hydroxyls is a necessary, but often very slow first enzymatic step. Anaerobic bacteria and archaea can accomplish this step much more readily using reductive dehalogenation.

Chlorinated hydrocarbons such as DDT, aldrin, dieldrin, and heptachlor, are very slowly broken down, persisting in aerobic soils for 20 or more years. In contrast, the organophosphate

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BOX 18.1

CONCENTRATIONS AND TOXICITY OF CONTAMINANTS IN THE ENVIRONMENT

As analytical instrumentation becomes more sophisticated, contaminants can be detected at much lower levels than was the case in the past. Since humans and other organisms can be harmed by almost any substance if large enough quantities are involved, the subject of toxicity and contamination must be looked at *quantitatively*. That is, we must ask *how much*, not simply *what*, is in the environment. Many highly toxic (meaning harmful in very small amounts) compounds are produced by natural processes and can be detected in the air, soil, and water—quite apart from any activities of humans.

The mere presence of a natural toxin or a synthetic contaminant may not be a problem. Toxicity depends on: (1) the *concentration* of the contaminant, and (2) the level of *exposure* of the organism. Thus, low concentrations of certain chemicals that would cause no observable effect by a single *exposure* (e.g., one glass of drinking water) may cause harm (e.g., cancer, birth defects) to individuals exposed to these concentrations over a long period of time (e.g., three glasses of water a day for many years).

Regulatory agencies attempt to estimate the effects of long-term exposure when they set standards for no-observable-effect levels (NOEL) or health-advisory levels (see Table 18.2). Some species and individuals within a species will be much more sensitive than others to any given chemical. Regulators attempt to consider the risk to the most susceptible individual in any particular case. For nitrate in groundwater, this individual might be a human infant whose entire diet consists of infant formula made with the contaminated water. For DDT, the individual at greatest risk might be a bird of prey that eats fish that eat worms that ingest lake sediment contaminated with DDT. For a pesticide taken up by plants from the soil, the individual at greatest risk might be an avid gardener who eats vegetables and fruits mainly from the treated garden over the course of a lifetime.

It is important to get a feel for the meaning of the very small numbers used to express the concentration of contaminants in the environment. For instance, concentrations are often given in parts per billion (ppb). This is equivalent to micrograms per kilogram or μg/kg. In water this would be μg/L (Table 18.2). To comprehend the number 1 billion imagine a billion golf balls: lined up, they would stretch completely around the Earth. One bad ball out of a billion (1 ppb) seems like an extremely small number. On the other hand, 1 ppb can seem like a very large number. Consider water contaminated with 1 ppb of potassium cyanide, a very toxic substance consisting of a carbon, a potassium, and a nitrogen atom linked together (KCN). If you drank just one *drop* of this water, you would be ingesting almost 1 trillion (10^{12}) molecules of potassium cyanide:

$$\frac{6.023 \times 10^{23}\ \text{molecules}}{1\ \text{mol}} \times \frac{1\ \text{mol}}{65\ \text{g KCN}} \times \frac{1\ \text{g KCN}}{10^{6}\ \mu\text{g KCN}} \times \frac{1\ \mu\text{g KCN}}{\text{L}} \times \frac{\text{L}}{10^{3}\ \text{cm}^{3}} \times \frac{\text{cm}^{3}}{10\ \text{drops}} = \frac{9.3 \times 10^{11}\ \text{molecules}}{\text{drop}}$$

In the case of potassium cyanide, the molecules in this drop of water would probably not cause any observable effect. However, for other compounds, this many molecules may be enough to trigger DNA mutations, endocrine disruptions, or the beginning of cancerous growth. Assessing these risks is still an uncertain business.

insecticides, such as parathion, are degraded quite rapidly in soils, apparently by a variety of organisms. Likewise, most herbicides (e.g., 2,4-D, the phenylureas, the aliphatic acids, and the carbamates) are readily attacked by a host of organisms, their breakdown is often slow enough that residual herbicidal effects may be exhibited on rotation or cover crops planted 4–6 months after the initial application. The triazines are degraded even more slowly, primarily by chemical action. Most organic fungicides are also subject to microbial decomposition, although the rate of breakdown of some is slow, causing troublesome residue problems. Furthermore, it cannot be assumed that once the original compound is degraded, the problem has been removed. In many cases, the degradation products may be as toxic as the original pesticide, thus adding to the long-term environmental hazards. Figure 18.10 illustrates the long time period required to remove the toxic hazard of an organic chemical (atrazine) if its movement through the soil and aquifer is slow and its degradation product (desethyl atrazine in this case) is both stable and also of environmental concern.

Plant Absorption and Breakdown

Plants assist in the degradation of pesticides and other xenobiotic contaminants in several ways. They may degrade the compounds in their rhizosphere soil by exuding enzymes that

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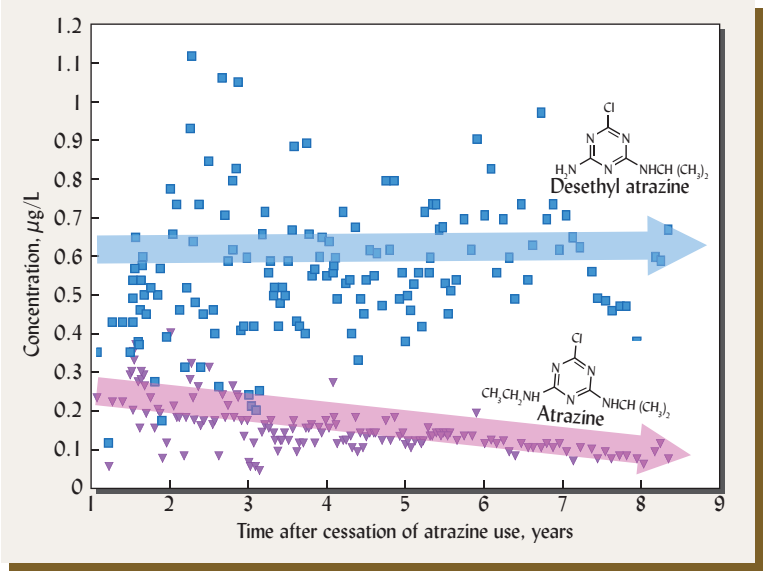

Figure 18.10 *Contamination of spring water in the nine years following the cessation of atrazine use by farmers in the Brévilles, France, watershed. Atrazine concentrations slowly decreased, but concentrations of its metabolite, desethyl atrazine, did not decrease. Both compounds are of concern for chronic environmental toxicity, very soluble in water, and moderately mobile through the soil under the near-neutral pH conditions of this area.* [Graph based on data in Barth et al. (2009)]

catalyze the breakdown of the compounds or by stimulating microorganisms to do so. Pesticides, especially systemic insecticides and most herbicides are commonly absorbed by plants via their roots or leaf surfaces. The absorbed chemicals may remain intact inside the plant, or they may be degraded. Often the pesticide is isolated by the plant inside cellular vacuoles where the degradation process takes place. Plants, being photoautotrophs, generally do not metabolize the pesticide molecule as a source of energy or carbon. Rather plant enzymes may cometabolize the pesticide into simpler breakdown products. As with microbial and chemical degradation, some plant metabolic degradation products are harmless, but others are even more toxic than the original chemical that was absorbed.

Understandably, society is quite concerned about pesticide residues found in the parts of plants that people eat, whether as fresh fruits and vegetables or as processed foods. Even foods produced without the use of synthetic pesticides (e.g., certified Organic) have been found to contain many pesticide compounds, albeit at significantly lower concentrations than found in conventionally produced foods. The use of pesticides and the amount of pesticide residues in food are strictly regulated by law to ensure human safety. Despite widespread concerns, there is little evidence that the small amounts of residues permissible in foods by law have had any ill effects on public health. However, routine testing by regulatory agencies has shown that about 1–2% of food samples tested contain pesticide residues above the levels legally permissible.

Persistence in Soils

The persistence of chemicals in the soil is the net result of all their reactions, movements, and degradations (see Figure 18.6). For example, organophosphate insecticides may last only a few days in soils. The widely used herbicide 2,4-D persists in soils for only two to four weeks. PCBs, DDT, and other chlorinated hydrocarbons may persist for 3–20 years or longer (Table 18.5). The persistence times of other pesticides and industrial organics fall generally between the extremes cited. The majority of pesticides degrade rapidly enough to prevent buildup in soils receiving normal annual applications. Those that resist degradation have a greater potential to cause environmental damage.

Continued use of the same pesticide on the same land can increase the rate of microbial breakdown of that pesticide. Apparently, having a constant food source allows a population buildup of those microbes equipped with the enzymes needed to break down the compound. This is an advantage with respect to environmental quality and is a principle sometimes applied in environmental cleanup of toxic organic compounds, but the breakdown may become sufficiently rapid to reduce a compound's effectiveness as a pesticide.

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Table 18.5
PERSISTENCE OF A SELECTED ORGANIC COMPOUNDS
Risks of environmental pollution are highest with those chemicals with greatest persistence.

Organic chemical	Persistence in soils
Chlorinated hydrocarbon insecticides (e.g., DDT, dieldrin)	3–20 yr
PCBs	2–10 yr
Triazine herbicides (e.g., atrazine and simazine)	1–2 yr
Glyphosate herbicide	6–20 mo
Benzoic acid herbicides (e.g., amiben and dicamba)	2–12 mo
Urea herbicides (e.g., monuron and diuron)	2–10 mo
Neonicotinoid insecticides (e.g., imidacloprid)	1-8 mo
Vinyl chloride	1–5 mo
Phenoxy herbicides (2,4-D and 2,4,5-T)	1–5 mo
Organophosphate insecticides (e.g., malathion and diazinon)	1–12 wk
Carbamate insecticides	1–8 wk
Carbamate herbicides (e.g., barban and CIPC)	2–8 wk

18.4 EFFECTS OF PESTICIDES ON SOIL ORGANISMS

Since pesticides are formulated to kill living things, it is not surprising that some of these compounds are also toxic to specific nontarget soil organisms. Many pesticides have been shown to affect certain soil organisms in ways that alter ecological balance and ecosystem function of soils. Fortunately, the diversity of soil organisms is so great that, most pesticides do not kill a significant proportion of the soil community. Chemicals used as soil fumigant present a major exception.

Fumigants

Fumigants are usually injected into the soil as bands of liquid or solid material. These compounds are designed to permeate or "fumigate" the soil in order to contact target pests (usually nematodes, fungi, or weed seeds) wherever they reside. Chemicals used as fumigants therefore are characterized by very high, but temperature dependent volatility; their volatility is generally lower in cooler soils. Also, as the chemical diffuses in vapor form, it moves much more rapidly through air-filled than through water-filled pores. Therefore, soil fumigation is most effective when the soil is quite *dry* and *warm* (Figure 18.11). On the other hand, nematodes live in water films around soil particles, so the chemical must also cross the partition between air and water phases to reach that target. Finally, the chemicals must also persist long enough to build up lethal concentrations that will kill the target organisms wherever they are located in the treated soil.

Most fumigants are either halogenated hydrocarbons (e.g., 1,3-dichloropropene and chloropicrin, the ingredients in Telone®) or sulfur-containing compounds that produce methyl isothiocyanates (e.g., sodium methyl dithiocarbamate, the main ingredient in Vapam®). Such fumigant compounds have very broad spectrum toxicity and effect on both the soil fauna and flora more drastically than do other pesticides. For example, 99% of the microarthropod population is usually killed by commercial fumigants, and it may take as long as two years for the population to fully recover. Fortunately, the recovery time for the microflora is generally much less.

Fumigation reduces the number of species of both flora and fauna, especially if the treatment is repeated, as is often the case where nematode control is attempted. At the same time, the total number of bacteria is frequently much greater following fumigation than before. This increase is probably due to the relative absence of competitors and predators following fumigation and to the carbon and energy sources left by dead organisms for microbial utilization. The decimation of the rhizosphere community of plant-beneficial micro- and mesoorganisms

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Figure 18.11 *Fumigants are volatile toxicants that permeate throughout the upper soil layers in vapor form and kill almost everything in the soils, pest and beneficial alike. They work most efficiently when the soil is warm and dry, as in this California field fumigated in preparation for tomato planting.* (Photo courtesy of Ray R. Weil)

generally leaves the next crop planted quite defenseless against any new infestation of pest or disease, creating a dependence on fumigants and calling into question the sustainability of the fumigation approach to soil borne pest control.

Effects on Soil Fauna

The effects of pesticides on soil animals vary greatly from chemical to chemical and from organism to organism. Nematodes are generally least affected, except by specific fumigants. Mites and springtails, two of the main groups of soil fauna at several trophic levels, vary in their sensitivity to insecticides, but many chemicals are quite toxic to these organisms.

Earthworms. Fortunately, many pesticides have only mildly depressing effects on earthworm numbers, but there are exceptions. Among insecticides, most of the carbamates (carbaryl, carbofuran, aldicarb, etc.) are highly toxic to earthworms. Among the herbicides, simazine is more toxic than most. Among the fungicides, benomyl is unusually toxic to earthworms. Toxicity may be expressed as more subtle than mortality. For example, one study showed the burrowing behavior of earthworms to be dramatically inhibited by a neonicotinoid insecticide applied to the soil (Figure 18.12).

Earthworm populations have been shown to adapt to some pesticides, such as the fungicide epoxiconazole. The earthworm populations may even rapidly develop an increased capacity to degrade the pesticide compound. However, such adaptive behavior may come at a metabolic cost to the earthworm population. The concentrations of pesticides in the bodies of the earthworms are closely related to the levels found in the soil. Thus, earthworms can magnify the pesticide exposure of birds, rodents, and other creatures that prey upon them.

Pesticides have significant effects on the numbers of certain predators and, in turn, on the numbers of prey organisms. For example, an insecticide that reduces the numbers of predatory

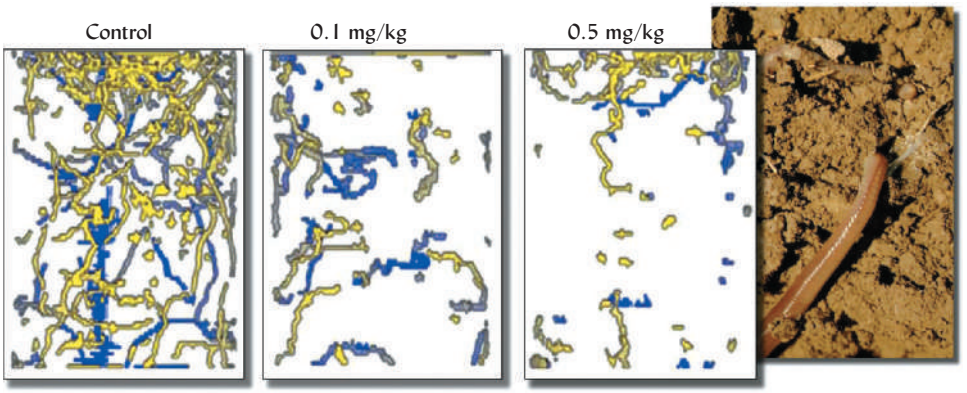

Figure 18.12 *Effects of organic pesticides on soil organisms may be more subtle than mortality. Here, the burrowing behavior of earthworms was shown to be dramatically inhibited by a neonicotinoid insecticide (imidacloprid) often used for seed treatments. The earthworms in the test columns were an endogeic (shallow burying) species* (Allolobophora Icterica) *collected from an apple orchard. Imidacloprid solutions were applied to give concentrations of 0.5 or 0.1 mg of the compound per kg of dry soil. The soil was a silt loam with 2.8% organic matter and pH 8.3.* [Burrow diagrams selected from Capowiez et al. (2006), photo of another earthworm species, courtesy of Ray R. Weil]

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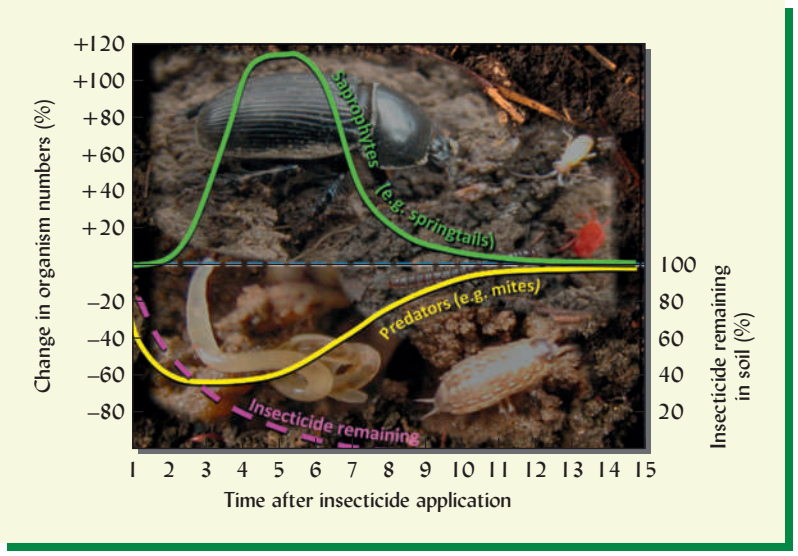

Figure 18.13 *The effects of an insecticide on the soil fauna can be both direct and indirect. Predators such as certain mites are often rapidly killed by a toxin, freeing their prey populations, such as saprophytic collembolan, from the constraints of predation. Depending on soil conditions and the persistence of the chemical, the time scale could be in days or months.* [Drawn from data and concepts in Edwards (1978) and El-Naggar and Zidan (2013). For effects of herbicides on soil organisms, refer to Rose et al. (2016)]

mites may stimulate numbers of springtails, which serve as prey for the mites (Figure 18.13). Such organism interaction is normal in most soils.

Effects on Soil Microorganisms

The overall levels of bacteria in the soil are generally not too seriously affected by pesticides. However, the organisms responsible for nitrification and nitrogen fixation are sometimes adversely affected. Insecticides and fungicides affect both processes more than do most herbicides, although some of the latter can reduce the numbers of organisms carrying out these two reactions. Certain pesticides may actually enhance biological nitrogen fixation by reducing the activity of protozoa and other organisms that are competitors or predators of the nitrogen fixing bacteria.

Fungicides, especially those used as fumigants, can have marked adverse effects on soil fungi and actinomycetes, thereby slowing down the humus formation in soils. Interestingly, however, the process of ammonification is often stimulated by pesticide use.

The negative effects of most pesticides on soil microorganisms are temporary, and after a few days or weeks, organism numbers generally recover. But exceptions are common enough to dictate caution in the use of the chemicals. Care must be taken to apply them only when alternate means of pest management are not available.

This brief overview of the behavior of organic chemicals in soils reemphasizes the complexity of the ecological changes that take place when new and exotic substances are added to our environment. Our growing knowledge of the soil processes involved certainly reaffirms the necessity for a thorough evaluation of potential soil ecological impacts prior to approval of new chemical products or the adoption of existing chemicals for use on the land.

18.5 REMEDIATION OF SOILS CONTAMINATED WITH ORGANIC CHEMICALS

Soils contaminated with organic pollutants are found throughout the world. The wide areas contaminated with organic pesticides are best addressed by modifying agroecosystems to enable the reduction or elimination of pesticides, or by using less toxic, less mobile, and more rapidly degradable pesticide compounds.

Perhaps more problematic, however, are sites where accidental spills or leakage of toxic organic materials have occurred or where, through the decades, organic wastes from industrial and domestic processes have been dumped on soils. The levels of such *acute contamination* are often sufficiently high that plant growth is restrained or even prevented. Pollutants can move into the

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groundwater, making it unfit for human consumption. Fish and wildlife may be decimated. The soil itself may become unsafe for human exposure. Because of public concerns, businesses and government are spending billions of dollars annually to clean up (**remediate**) these contaminated soils. We shall consider a few of the methods in use and under development in the rapidly evolving soil remediation industry. In general, efforts to remediate polluted soils face the need to compromise between speed and certainty that cleanup standards will be met on one hand, and expense and disruption of the site on the other (Figure 18.14). In many cases of relatively mild contamination, the soil ecosystem may be able to destroy the contaminant and heal itself, unaided, by the process of **natural attenuation**. Natural attenuation may allow the soil ecosystem to recover its function and diversity over a reasonable period using any or all of the chemical, physical, and biological processes that were illustrated in Figure 18.6. However, in other cases, the contamination may be so serious that natural attenuation will occur too slowly to be a practical solution and more active technological interventions may be called for.

Physical and Chemical Methods

The earliest and still widely used methods of soil remediation involve physical and/or chemical treatment of the soil, either in place (in situ) or by moving the soil to a treatment site (ex situ).

Ex Situ Treatment. Ex situ treatment may involve excavating the soil to treatment containers where it may be incinerated to drive off volatile chemicals and to destroy other pollutants by high-temperature chemical decomposition. Water-soluble and volatile chemicals may also be removed by pushing or pulling air or water through the soil by vacuum extraction or leaching. Such treatments are usually quite effective in removing or destroying the contaminants, but are expensive, especially if large quantities of soil must be excavated and treated. And, of course, the site is highly disrupted and the treated soil is destroyed as a living system and must be either replaced on the site or deposited in a landfill. The costs, in terms of money and energy, for excavation and hauling large volumes of soil can be prohibitive.

In Situ Treatment. In situ treatments are usually preferred if viable technologies are available. The soil is left in place, thereby reducing excavation, treatment, and disposal costs and providing greater flexibility in future land use. The contaminants are either removed from the soil (*decontamination*) or are sequestered (*bound up*) in the soil matrix (*stabilized*). Decontamination in situ involves some of the same techniques of water flushing, leaching, vacuum extraction, and heating used in ex situ processes.

Surfactants. Water washing treatments are not effective for oils and other nonpolar compounds that are repelled by water. To help remove such compounds, compounds called *surfactants* (similar to detergents) maybe sprayed onto the soil surface or injected into the soil. As the surfactants move

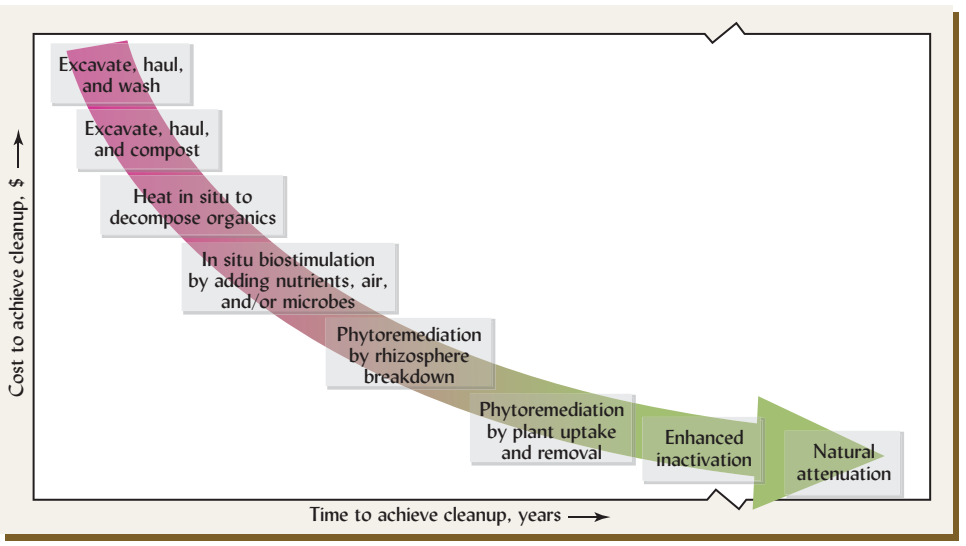

Figure 18.14 *A wide range of methods is available to remediate (clean up) polluted soils. At one extreme are remediation techniques that are very expensive and disruptive, but usually quite rapid. Technologies at the other extreme may be quite inexpensive and nondisruptive, but usually take much more time to accomplish the cleanup.* [Modified from Reynolds et al. (1999)]

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downward in the soil, they dissolve organic contaminants, which can then be pumped out of the soil as in the water washing systems. Surfactants can also be used to make hydrophobic contaminants more available to bacterial enzymes that are able to degrade them either in situ or ex situ.

Organoclays. Certain surfactants may also be used to immobilize or stabilize soil contaminants. They are positively charged and through cation exchange can replace metal cations on soil clays. For example, one group of such surfactants, quaternary ammonium compounds (QACs), has the general formula $(CH_3)_3NR^+$, where R is an organic alkyl or aromatic group. The positive charges on QACs stimulate cation exchange by reactions such as the following, using a monovalent exchangeable cation such as K^+ as an example:

$$\underset{\text{Untreated clay}}{\boxed{\text{Colloid}}}\ K^+ + \underset{\text{QAC}}{(CH_3)_3NR^+} \longrightarrow \underset{\text{Organoclay}}{\boxed{\text{Colloid}}}\ (CH_3)_3NR^+ + K^+ \qquad (18.1)$$

The resulting products, known as *organoclays*, have properties quite different from the untreated clays. They attract rather than repel nonpolar organic compounds. Thus, the injection of a QAC into the zone of groundwater flow can stimulate the formation of organoclays and thereby immobilize soluble organic groundwater contaminants, holding them until they can be degraded (Figure 18.15).

Distribution Coefficients K_d. As we learned in Section 8.12, the degree of sorption of organic compounds by soil colloids is commonly indicated by the coefficient of distribution K_d, the ratio between the sorbed and solution portions of the organic compound.

$$K_d = \frac{(\text{mg contaminant/kg soil})}{(\text{mg contaminant/L solution})} \qquad (18.2)$$

The K_d for the adsorption of many nonpolar organic compounds on untreated clays is very low because the clays are hydrophilic (water-loving) and their adhering water films repel the hydrophobic, nonpolar organic compounds (Figure 18.16). Surface soil horizons containing significant quantities of humus often exhibit a much higher K_d because of the sorption of the organic contaminant into the organic matter coatings. This is the reason that K_{oc} is often a better measure of a compound's tendency to become immobilized in various surface soils. Deeper soil layers, especially near and below the water table, generally contain little humus, and so have limited capacity to immobilize organic contaminants.

In contrast, organoclays effectively sorb organic contaminants, leaving little in the soil solution, thereby reducing their movement into the groundwater and eventually into streams

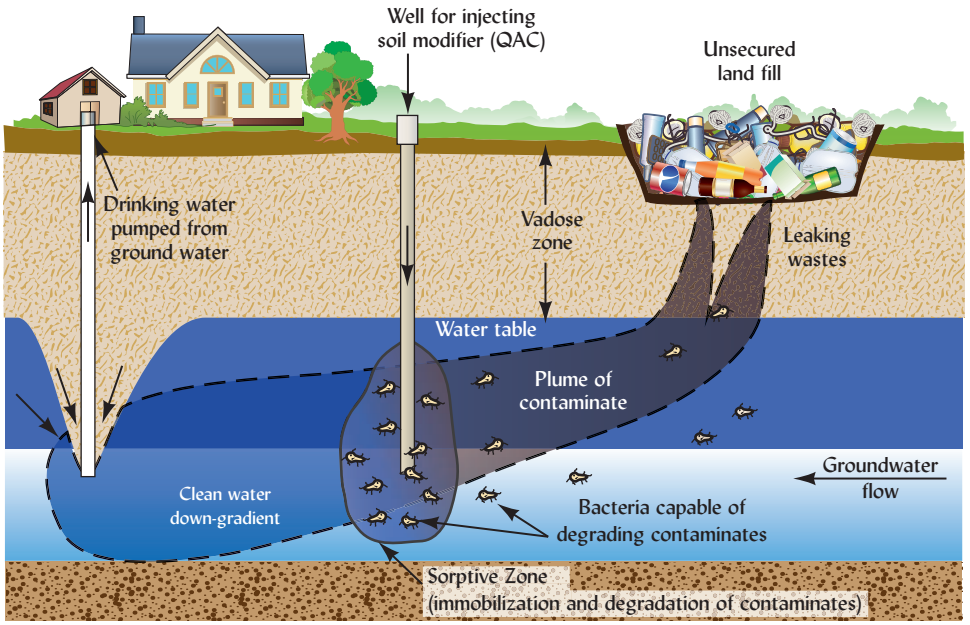

Figure 18.15 *How a combination of a quaternary ammonium compound (QAC), hexadecyltrimethylammonium, and bioremediation by degrading bacteria could be used to hold and remove an organic contaminant. The pollutant is moving into groundwater from a buried waste site. The QAC reacts with soil clays to form organoclays and soil organic matter complexes that adsorb and stabilize the contaminant, giving microorganisms time to degrade or destroy it.* [Diagram courtesy of Ray R. Weil using concepts from Xu et al. (1997)]

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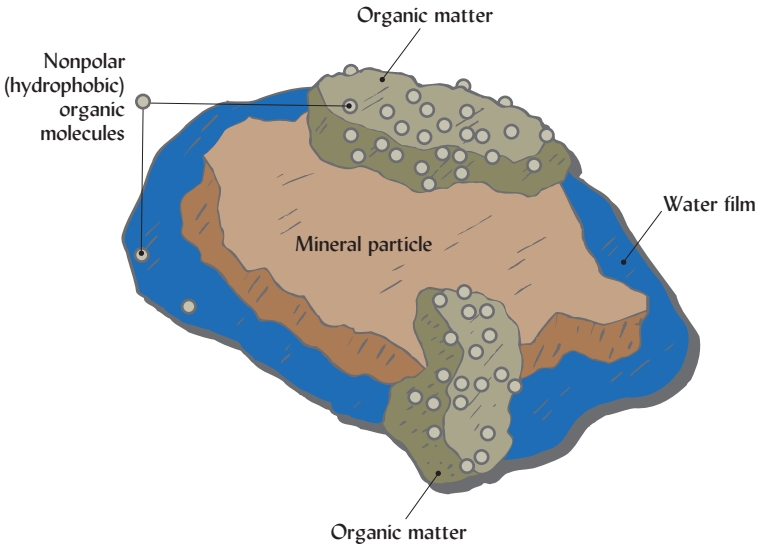

Figure 18.16 *Because mineral colloids in soils are nearly always surrounded by at least a thin film of water, hydrophobic organic molecules tend to sorb onto humus more readily than clay. The nonpolar organic molecules cannot compete with the polar water molecule for a place on the charged mineral surfaces. This is one reason why, for a specific organic contaminant, the* K_{oc} *is more consistent than the* K_d *in characterizing the tendency to be held by various soils.* (Diagram courtesy of Ray R. Weil)

or drinking water. Consequently, the K_d values of organic contaminants on organoclays are commonly 100–200 times those measured on the untreated clays. Table 18.6 shows K_d values for some common organic contaminants on organoclays and indicates the very high sorbing power of the newly created sorbants. Their tenacity is complemented by the very strong complexation of organic compounds by soil organic matter. Organoclays thus offer promising mechanisms for holding organic soil pollutants until they can be destroyed by biological or physicochemical processes.

Bioremediation[4]

Even for many heavily contaminated soils, there is a biological alternative to incineration, soil washing, and landfilling—namely, **bioremediation**. Simply put, this technology uses enhanced plant and/or microbial action to degrade organic contaminants into harmless metabolic products. Analysis of microbial DNA has shown that degradation of contaminants in soils is almost always the work of genetically diverse *consortia* of many organisms, rather than just one or two bacterial species. Petroleum constituents, including the more resistant PAHs, as well as several synthetic compounds, such as pentachlorophenol (PCP) and TCE, can be broken down, primarily by soil bacteria and so-called white-rot fungi. Bioremediation is usually accomplished in situ, but polluted soil may also be excavated and treated ex situ—that is, hauled to a treatment site where such techniques as high-temperature composting may be used to destroy the organic contaminants in the soil (Figure 18.17).

Bioaugmentation. In most cases, the remediation process depends on organisms native to the soil. In certain cases, the biodegradation of contaminants can be accelerated if microbes specifically selected for their ability to degrade the contaminants are introduced into the polluted soil zone to *augment* the natural microbial populations. This approach is called **bioaugmentation**. Some success has been achieved by inoculating contaminated soils with improved organisms that can degrade the pollutant more readily than can the native population. Although genetic engineering may prove useful in making "superbacteria" in the future, most inoculation has been achieved with naturally occurring organisms. Organisms isolated from sites with a long history of the specific contamination or grown in laboratory culture on a diet rich in the pollutant in question tend to become acclimated to metabolizing the target chemical.

For example, certain bacteria have been identified that can detoxify perchloroethene (PCE), a common, highly toxic groundwater pollutant that is suspected of being a carcinogen. Scientists can inoculate the anaerobic subsoil or groundwater zone with these organisms to expedite reductive dechlorination. This step-by-step removal of the four chlorines from the PCE produces ethylene, a gas that is relatively harmless to humans.

[4]For reviews of the theories and technologies regarding this topic, see Wise et al. (2000), Eccles (2007), or Hazen (2008).

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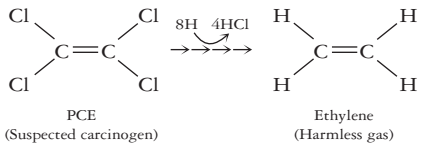
Table 18.6
SORPTION OF FIVE ORGANIC COMPOUNDS ON ORGANOCLAYS FORMED BY TREATING VARIOUS CLAYS WITH A QUATERNARY AMMONIUM COMPOUND (QAC)
High K_d values suggest high retention of the pollutants and low concentration in the soil solution. Kaolinite and illite had low tendencies to form organoclays, and sorption coefficients varied among the compounds.

Clay	CEC of untreated clay, $cmol_c$/kg	Organic C in organoclay, %	K_d of organic contaminants on organoclays				
			Benzene	Toluene	Ethylbenzene	Propylbenzene	Naphthalene
Illite	24	2.5	39	77	156	—	1270
Vermiculite	80	16.4	68	169	448	1618	1387
Smectite	130	23.0	184	319	583	1412	4818
Kaolinite	4	1.0	3	7	21	—	—

Data from Jaynes and Boyd (1991).

Figure 18.17 *Hot water vapor rises in cold winter air as windrows of high-temperature compost are mixed and aerated by a special compost-turning machine in order to accelerate the breakdown of organic compounds. The method can hasten the degradation of organic pollutants in soil material excavated from a contaminated site, mixed with decomposable organic materials, and made into windrows.* (Photo courtesy of Ray R. Weil)



(18.3)

While inoculation with strains of specialized bacteria often produces rather spectacular results in the lab, such bioaugmentation with specially selected bacteria only rarely makes a significant difference in contaminant degradation rates in the field. There are two reasons for the limited effect. First, the introduced bacteria usually do not survive long in the competitive environment in contaminated field soils and groundwater; they rapidly die out and end up as food for the native bacteria. Second, little enhancement is usually seen from inoculation because most field soils and ground waters naturally already contain populations of bacteria quite capable of doing the job—if conditions are right. Therefore, as the science and practice of bioremediation has advanced, most attention has been focused on ways to make conditions in the soil right for contaminant degradation.

Biostimulation. The use of bioremediation technology that assists the naturally occurring microbial populations in breaking down chemicals is called **biostimulation**. Usually, the soil

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naturally contains some bacteria or other microorganisms that can degrade the specific contaminant. Even so, the rate of natural degradation may be far too slow to be effective.

Once it is determined that organisms are present that are capable of using the contaminant as a carbon source, biostimulation techniques work to address one or more of four fundamental conditions that may limit the effective rate of contaminant biodegradation:

1. *Inaccessibility of the contaminant* to the organisms that could degrade it. We have already mentioned the practice of adding surfactants to make contaminants accessible to bacterial degradation by desorbing mineral-bound contaminants or by dissolving hydrophilic contaminants in a way that allow bacteria to attach themselves to the molecules.
2. *Lack of nutrients* may restrict organism growth and metabolism. This is especially likely in low organic matter sandy soils and where the contaminant is a hydrocarbon such as a petroleum product. In these cases, adding fertilizer (especially nitrogen and phosphorus) in suitable form may greatly stimulate biodegradation rates. A classic example from oil-spill cleanup technology is described below.
3. *Electron donor* substances (food) may be inadequate for rapid bacteria growth. In some cases readily available energy sources such as molasses (for respiring organisms) or methane (for methanotrophs) have been added with success (see below).
4. *Electron acceptor* substances may be inadequate for effective metabolism. For aerobic breakdown this situation may call for adding oxygen by pumping air into the contaminated soil or groundwater zone. For other organisms, pumping in nitrate may allow denitrifiers to degrade the compound.

Finally, the *habitat* may be inhospitable or too toxic for biodegradation to take place because either: (1) levels of the target contaminant are so high that it is toxic to even the organisms that can degrade it, or (2) the site is cocontaminated with another substance, perhaps a heavy metal (see Sections 18.6 and 18.7), in such concentrations that the potential biodegradation organisms cannot thrive, or even survive. In such cases in situ bioremediation may not be possible and the soil may have to be excavated and removed from the site. The heavily contaminated soil may then be diluted with clean soil or partially washed for biodegradation to proceed, or the heavily contaminated soil may have to be landfilled as a hazardous waste.

Both growth rate and metabolic rate of the organisms capable of using the contaminant as a carbon source are often limited by insufficient mineral nutrients, especially nitrogen and phosphorus (see Section 12.3 for a discussion of the C/N ratio in organic decomposition). Special fertilizers have been formulated and used successfully to greatly speed up the degradation process. One such fertilizer is an oil-in-water microemulsion of urea, lauryl phosphate, and an emulsion stabilizer. It acts not only as a supplier of nutrients, but also as a surfactant that can enhance interaction between microbes and the organic contaminants. It received its first major test in Alaska in 1989.

Oil Spill Cleanup. The 30 or more different genera of bacteria and fungi known to degrade hydrocarbons are found in almost any soil or aquatic environment. But they may need help. In 2012, the British Petroleum Deepwater Horizon offshore drilling rig explosion resulted in a huge amount of oil leaking into the Gulf of Mexico and washing up the surrounding beaches. In the warm, nutrient rich Gulf of Mexico, naturally occurring bacteria rapidly degraded most of the lighter components of the crude oil within a few weeks of the leak being sealed. The only help they got from humans was the application of dispersant chemicals that broke the oil into tiny droplets that the bacteria could better access. Fortunately, soil Bacteria and Archaea helped the beaches and wetlands recover from the oil spill much faster than scientists had expected.

The situation with the previously largest U.S. oil spill—the 1989 Exxon Valdez oil spill in Alaskan waters was quite different. The spill took place when a supertanker broke up and sank just a short distance from the pristine shores of Prince William Sound. The pebble beaches were heavily contaminated with crude oil driven up by a large storm. The cold and nutrient poor water and pebble beaches were not conducive to bacterial growth. Help was needed. It came in the form of the first large-scale successful bioremediation by fertilization.

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The oil-eating bacteria had the carbon and oxygen they needed (electron donor and acceptor, respectively), but they were starved for nitrogen and phosphorus. The oil-soaked beaches (pebbly Entisols) were sprayed with a special 7.4% N and 0.7% P fertilizer named Inipol EAP 22. This fertilizer was made from a base of oleic acid (a biodegradable oliophilic organic) and contained tri(laureth-4)-phosphate (the phosphorus source and a surfactant similar to those found in many shampoos), urea (a soluble nitrogen source), and 2-butoxyethanol (a surfactant and emulsifier that, though toxic, proved to be biodegradable).

The fertilizer was formulated to be oliophilic (soluble in oil but not in water) so that it would stay with the oil and not only provide N and P to the bacteria but also emulsify and disperse the oil to make it more physically accessible to biodegradation (and to avoid contributing to eutrophication of Prince William Sound). Within a few weeks, and despite the cold temperatures, most of the oil in the test area was degraded (Figure 18.18).

In Situ Biostimulation Techniques. Other situations call for the use of other bioremediation techniques in situ. In some cases, low soil porosity or water saturation causes oxygen deficiency that limits microbial activity. Techniques have been developed that use in situ bioremediation to clean up oxygen-deficient soils and associated groundwater contamination. For example, organic-solvent-contaminated soils have been bioremediated (Figure 18.19) by piping in a mixture of air (for oxygen), methane (to act as a carbon source to stimulate specific bacteria), and phosphorus (a nutrient that is needed for bacteria growth). The design and likely success of such schemes is very dependent on such properties as soil texture. Coarse-textured, sandy soils are much easier to bioremediation because their high permeability allows nutrients and other additives to be relatively easily pumped through the soil to the contaminated zone. Fine-textured soil with high clay contents and low permeability are much more difficult for such projects.

Phytoremediation

Green plants can also participate in bioremediation, in which case the process is termed **phytoremediation**. For several decades, plant-based systems have been used for the removal of municipal wastewater contaminants (Sections 16.5 and 13.8). More recently, this concept has been extended to industrial soil pollutants and to the removal of organic and inorganic pollutants from shallow groundwater.

The most basic and simplest form of phytoremediation is **phytostabilization**, in which almost any kind of plant cover is grown in order to stabilize the contaminant and reduce its movement into the wider environment. In phytostabilization plants provide several services: (1) they provide groundcover to reduce the movement of contaminated soil and dust by water and wind erosion; (2) their transpiration reduces the amount of rainwater moving through the contaminated soil and thus also reduces the production of contaminated leachate; (3) their plants may absorb the contaminant and sequester it in their root systems; and (4) the plant root may cause the precipitation of the contaminant in the rhizosphere. The main shortcoming of the phytostabilization approach is that the contaminant is not removed or destroyed, but remains in the soil.

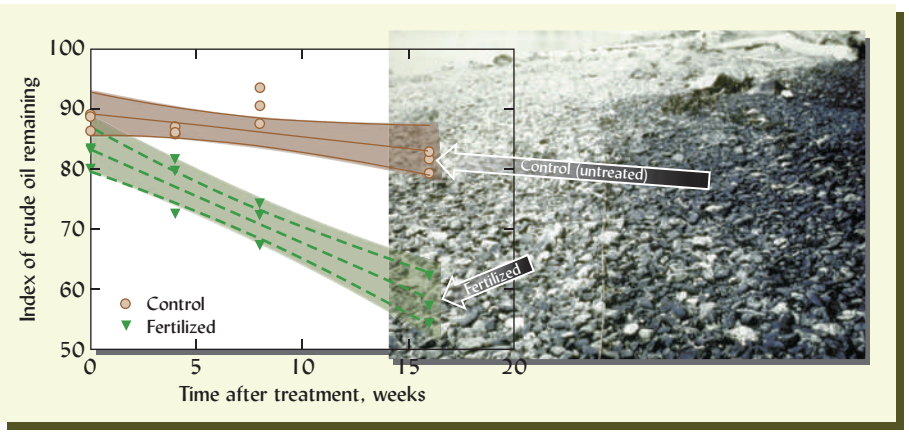

Figure 18.18 *Bioremediation of crude oil from the Exxon Valdez oil spill off the coast of Alaska. The oil contaminating the pebbly beach soils was degraded by indigenous bacteria when an oil-soluble fertilizer containing nitrogen and phosphorus was sprayed on the beach (green data points in graph on the left). The control sections of the beach (brown data points) were left unfertilized for almost 11 weeks. By then the effect of the fertilization was so dramatic that a decision was made to treat the control sections as well. Therefore, the regression line for the control plots probably includes some remediation by fertilizer in the last set of measurements. The photo (right) shows the clear delineation between the oil-covered control section and the fertilized parts of the beach.* [Graph regressions using selected data in Bragg et al. (1994); Photo courtesy of P.H. Pritchard, USEPA, Gulf Ecology]

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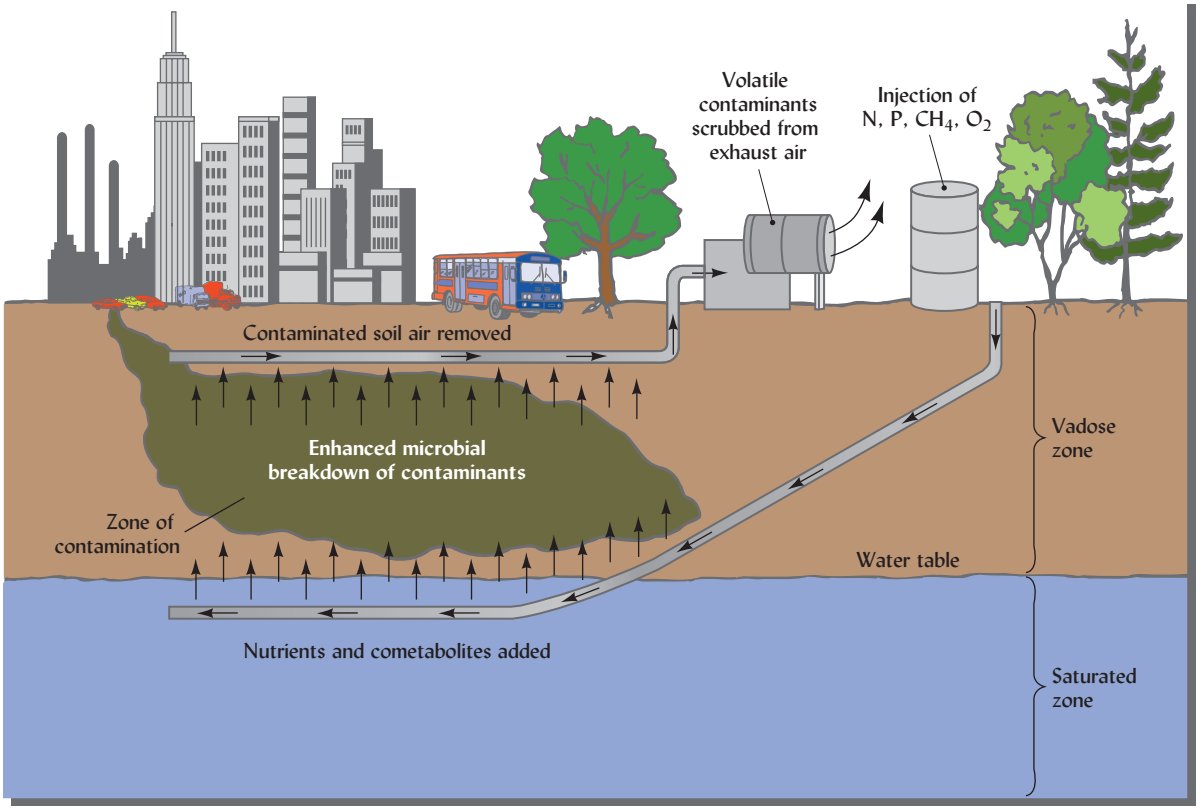

Figure 18.19 *In situ bioremediation of soil and groundwater contaminated with volatile organic solvents. The scheme illustrated is typical of the biostimulation approach to soil remediation. Breakdown of the organic contaminant is stimulated by adding such components as nutrients, oxygen, and cometabolites that improve the soil environment for the growth of native bacteria capable of metabolizing the contaminant. In this instance, methane (CH_4) is added intermittently as a substrate for certain methane-oxidizing bacteria which multiply rapidly and turn to the solvent as a carbon source whenever methane is not available. The nutrients are added and the contaminated soil air is removed by perforated pipes inserted by horizontal well-drilling techniques. Such biostimulation schemes can significantly cut the time and cost for cleanup of contaminated soils.* [Based on Hazen (1995)]

At a more sophisticated level, certain plants have been found or developed through selection that can quite effectively remove, accumulate, and/or degrade specific soil contaminants. Such phytoremediation uses plants in two fundamentally different ways (Figure 18.20). In the first, plant roots take up the pollutant from the soil. The accumulation of unusually high concentrations of a contaminant in the aboveground plant biomass is called **hyperaccumulation.** Hyperaccumulating plants take up and tolerate very high concentrations of a particular contaminant, most commonly a toxic metal such as cadmium or nickel (see Section 18.9), but also certain organics such as TNT. Hyperaccumulation allows the contaminant to be removed by harvesting the plant tissue. The harvested plant material may be so concentrated in the contaminant that it must be treated as hazardous material. Fortunately, certain organic contaminants, plants have been found that can metabolize the accumulated contaminant into harmless by-products.

A second type of cleanup using plants is called **enhanced rhizosphere phytodegradation**. In this process, the plants do not take up the contaminant. Instead, the plant roots excrete into the soil carbon compounds that serve as microbial substrates and growth regulators (see Section 11.7). These compounds stimulate the growth of the rhizosphere bacteria that, in turn, degrade the organic contaminant. The transpiration of water by the plant causes soil water, with its load of dissolved contaminant molecules, to move toward the roots, thus increasing the efficiency of the rhizosphere reactions. The process can be further enhanced by teaming the plants with appropriate symbiotic mycorrhizal fungi (see Section 11.9).

Some plant species are definitely better than others at stimulating the degradation of specific compounds in their rhizospheres. Many plant species, domesticated and wild, have been used in such phytoremediation. Prairie grasses can stimulate the degradation of petroleum

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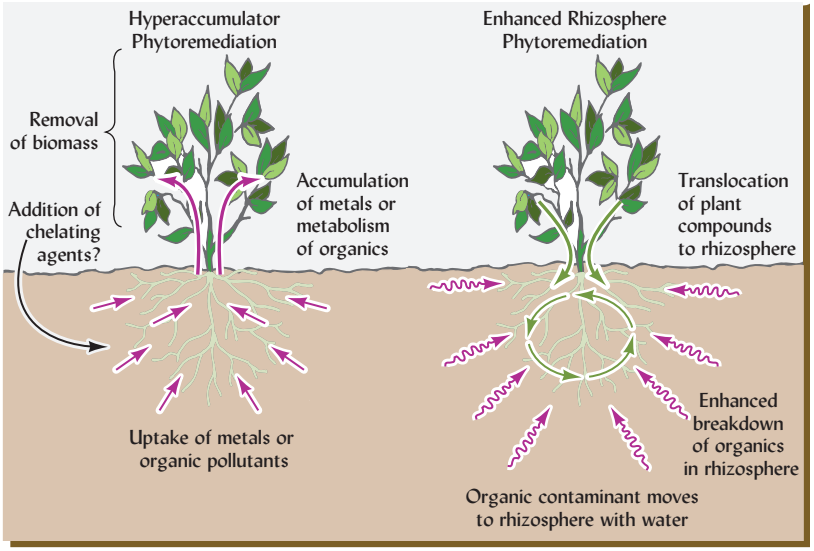

Figure 18.20 *Two approaches to phytoremediation—the use of plants to help clean up contaminated soils.* (Left) *Hyperaccumulating plants take up and tolerate very high concentrations of an inorganic or organic contaminant. In the case of metal contaminants, the addition of chelating agents may increase the rate of metal uptake, but can add a major expense and may allow metals to migrate below the root zone.* (Right) *In enhanced rhizosphere phytoremediation, the plants do not take up the contaminant. Instead, the plant roots excrete substances that stimulate the microbes in the rhizosphere soil, speeding their degradation of organic contaminants. Transpiration-driven movement of water and dissolved contaminants to the enhanced rhizosphere zone improves the system's effectiveness.* (Diagram courtesy of Ray R. Weil)

products, including PAHs, and spring wildflower plants in Kuwait were found to degrade the hydrocarbons in oil spills. Fast-growing hybrid poplars can remove ammunition compounds, such as TNT, as well as some pesticides and excess nitrates. Figure 18.21 illustrates how phytoremediation hastened the cleanup of two oil-contaminated sites under cold-weather conditions.

Phytoremediation is particularly advantageous where large areas of land are contaminated with only moderate concentrations of organic pollutants located at shallow depths in the soil. Phytoremediation causes little site disturbance and is relatively inexpensive, but also commonly takes a longer time to remove large quantities of contaminants than do the more costly engineering procedures.

Effect of Aging on Bioavailability of Chemicals in Soil

As we have seen, when an organic contaminant is added to soil, biological and chemical processes begin to degrade the contaminant so its total concentration declines steadily for weeks, months, or years, depending on its half-life. Researchers have found, however, that many organic contaminants may undergo an aging process in the soil, whereby over time the contaminant becomes less and less subject to decomposition even though relatively high concentrations can still be detected by laboratory analyses. When soil scientists use bacteria, earthworms, plants, or animal feeding in **bioassays** to determine the effect of the compound on living organisms, the initial period of degradation is usually paralleled by a similar period of declining biological activity. In other words, the ***bioavailability*** at first parallels the contaminant concentration. However, after more time (usually years) has elapsed, the bioavailability continues to decline even though the concentration does not (Figure 18.22, *left*).

The contradiction between the trends of concentration and bioavailabiliity for a contaminant in soil may be explained by strong, nearly irreversible *sorption* by Fe, Al oxides or silicate clays, or by *chemical complexation* with organic matter. In addition, contaminant molecules may become *physically isolated* in three ways. First, the contaminant molecules may become *trapped in soil nanopores*, tiny pore spaces 1–100 nm in diameter. These pores, within the humus and clay colloids, are large enough to shelter the contaminant molecule ((*a*) in Figure 18.22, *right*), but too small for entry of bacteria or even their extracellular enzymes that would otherwise be capable of attacking the contaminant. Second, the contaminant molecules may diffuse into or be absorbed onto the solid structure of a humus particle, where, again, they would not be exposed to living cells or their enzymes ((*b*) in Figure 18.22, *right*). Third, contaminant molecules may become buried, or occluded, under precipitated mineral coatings, again isolating them from biological interactions ((*c*) in Figure 18.22, *right*). Pollutant molecules trapped by any of these mechanisms may offer little risk of environmental mobility or biological toxicity

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	Bare soil (natural attenuation)		Vegetated and fertilized soil	
Time after spill	Total petroleum hydrocarbons	Bacterial populations	Total petroleum hydrocarbons	Bacterial populations
Weeks	mg/kg	Number/g	mg/kg	Number/g
0	8300	n.a.	8300	n.a.
8	5700	n.a.	1900	n.a.
34	2300	3.55×10^5	600	1.02×10^8

Figure 18.21 *Rhizosphere-enhancement phytoremediation of oil contaminated soils. The photo shows test plots adjacent to oil storage tanks in Arkansas, USA, where an accidental spill occurred. Two cool-season grasses (tall fescue and ryegrass) were seeded on the enhanced rhizosphere plots in January, and the photograph was taken five months later. The data are for attenuation of total petroleum hydrocarbons (TPHs) in another similar oil-contaminated soil near Fairbanks, Alaska. Where plant roots created rhizosphere conditions in much of the soil volume, a 75% reduction in TPH concentration was achieved in less than eight weeks. In the unvegetated plots, natural attenuation had not achieved this level of cleanup even after 34 weeks. Fertilizer was used to stimulate the growth of plants, whose roots, in turn, enhanced the growth and activity of microorganisms, which finally provided the enzymatic activity to break down the petroleum compounds in the soil. Note that bacteria were nearly 300 times as numerous in the vegetated and fertilized enhanced rhizosphere plots as in the unvegetated natural attenuation control plots.* [Photo courtesy of Duane Wolf, University of Arkansas; Data selected from Reynolds et al. (1999)]

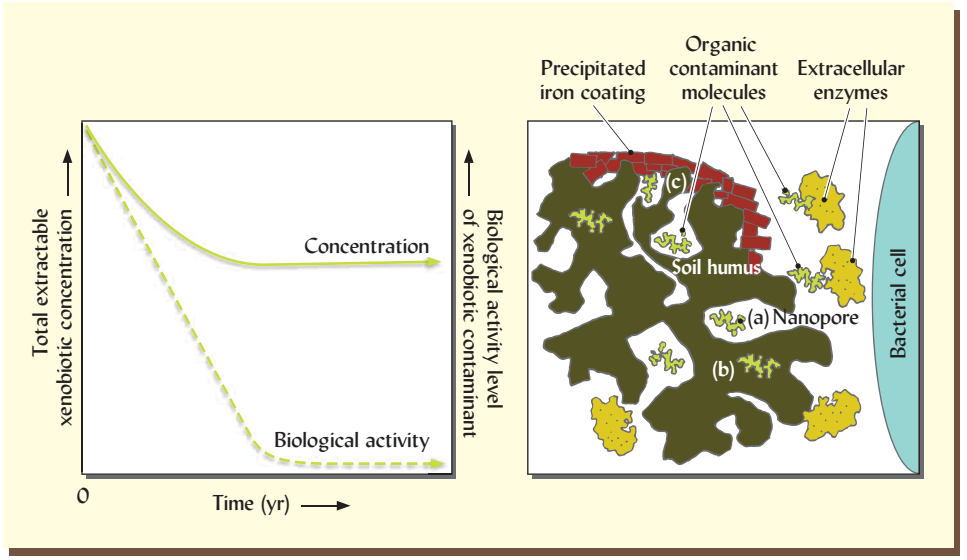

Figure 18.22 *The effect of aging on soil contaminant bioavailability. (Left) Over time, chemical and physical "aging" interactions with soil colloids may slow degradation of organic contaminants, even while bioavailability continues to decline. (Right) The decline in bioavailability can be due to irreversible sorption by mineral colloids and chemical complexation by humus, but some contaminant molecules (b) may become physically isolated in nanopores (a) too small for bacteria or large, extracellular enzyme molecules. Pollutants so held are not likely to move to groundwater or affect soil or food chain organisms.* [Diagrams courtesy of Ray R. Weil, based on concepts in Alexander (2000) and Stokes et al. (2005)]

even if their total concentration in the soil remains high. Because of this aging process, some scientists believe that environmental cleanup standards should be based on a contaminant's measurable bioavailability rather than on its total concentration. Therefore, regulations that set standards for total soil pollutant concentrations may be more strict (and more expensive) than is actually necessary to achieve an acceptably low level of risk. The question of whether to base environmental standards on the total amount of a compound present or on the bioavailability of the compound also applies to contamination by inorganic substances such as toxic metals, the topic of the following section.

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18.6 SOIL CONTAMINATION WITH TOXIC INORGANIC SUBSTANCES[5]

The toxicity of inorganic contaminants released into the environment every year is now estimated to exceed that from organic and radioactive sources combined. A fair share of these inorganic substances ends up contaminating soils. The greatest problems most likely involve mercury, cadmium, lead, arsenic, nickel, copper, zinc, chromium, molybdenum, manganese, selenium, fluorine, and boron. To a greater or lesser degree, all of these elements are toxic to humans and other animals. Cadmium and arsenic are extremely poisonous; mercury, lead, nickel, and fluorine are moderately so; boron, copper, manganese, and zinc are relatively lower in mammalian toxicity. Table 18.7 provides background information on the uses, sources, and effects of some of these elements. Although the toxic metals and metalloid elements (see periodic table, Appendix B) are not all, strictly speaking, "heavy" metals (more dense than iron), for the sake of simplicity this term is often used in referring to them.

Sources of the Contaminants

Inorganic chemicals from many sources contaminate and accumulate in soils. The burning of fossil fuels, metal ore smelting (Figure 18.23), and many manufacturing processes release tons of these elements into the atmosphere, which can carry the contaminants and later deposit them on the vegetation and soil many kilometers downwind. Lead, nickel, and boron

Table 18.7
SOURCES AND HEALTH EFFECTS OF SELECTED INORGANIC SOIL POLLUTANTS

Chemical	Major uses and sources of soil contamination	Organisms principally harmed[a]	Human health effects
Arsenic	Pesticides, plant desiccants, animal feed additives, coal and petroleum, mine tailings, detergents, and irrigation water	H, A, F, B	Cumulative poison, cancer, skin lesions
Cadmium	Electroplating, pigments, plastic stabilizers, batteries, and phosphate fertilizers	H, A, F, B, P	Heart and kidney disease, bone embrittlement
Chromium	Stainless steel, chrome-plated metals, pigments, refractory brick manufacture, and leather tanning	H, A, F, B	Mutagenic; also essential nutrient
Copper	Mine tailings, fly ash, fertilizers, windblown copper-containing dust, and water pipes	F, P	Rare; mental problems, fatigue; essential nutrient
Lead	Combustion of oil, gasoline, and coal; lead-acid batteries; iron and steel production; solder in water-pipes; paint pigments	H, A, F, B	Brain damage, convulsions
Mercury	Pesticides, catalysts for synthetic polymers, metallurgy, and thermometers; from coal burning	H, A, F, B	Nerve damage
Nickel	Combustion of coal, gasoline, and oil; alloy manufacture; electroplating; batteries; and mining	F, P	Lung cancer
Selenium	High Se geological formations and irrigation wastewater in which Se is concentrated	H, A, F, B	Deformities; essential nutrient
Zinc	Galvanized iron and steel, alloys, batteries, brass, rubber manufacture, mining, and old tires	F, P	Rare; essential nutrient

[a]H = humans, A = animals, F = fish, B = birds, P = plants.

[5]Several reviews of metal contamination and remediation of soils are worth reading (Su et al., 2014; Wu et al., 2010). Heavy metal contamination of food grown in China is discussed in Zhang et al. (2015). The basic biogeochemistry of metals is detailed by Adriano (2001).

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Figure 18.23 *A partially denuded hillside just downwind from a copper smelter in Anaconda in Montana, USA. For almost a century, the heavy metal-laden fumes contaminated this area with copper, zinc, nickel, and other metals to levels that are highly toxic to most plants and many other organisms, decimating the ecosystems of the area. Note the serious erosion that has resulted from the devegetation, despite the recent invasion of the area by a few metal-tolerant plant species.* (Photo courtesy of Ray R. Weil)

are gasoline additives that are released into the atmosphere and carried to the soil through rain and snow. Today the main use for lead is in lead-acid batteries for vehicles, but many soils continue to become contaminated with lead from the peeling of old painted surfaces. Boron as the mineral borax is used in detergents, fertilizers, and forest fire retardants, all of which commonly reach the soil. Phosphate fertilizer and limestone, two widely used soil amendments, usually contain small quantities of cadmium, copper, manganese, nickel, and zinc. Cadmium is used in plating metals and in the manufacture of rechargeable batteries. Arsenic was for many years used as a wood preservative as well as an insecticide on cotton, tobacco, fruit crops, lawns, and as a defoliant or vine killer. Some of these mentioned elements are found as constituents in specific organic substances and in domestic and industrial sewage sludge. Mercury is released from gold mining and chemical manufacturing industries, as well as from burning certain types of coal.

Accumulation in Soils

Some of these toxic metals are being released to the environment in increasing amounts, while emissions of others (most notably lead, because of changes in gasoline formulation) are decreasing. Unlike most organic contaminants, the inorganic toxins do not decompose and degrade; rather they usually remain in the soil and so accumulate from year to year. In many places, the metal contamination is historical, resulting from polluting activities that are no longer practiced. Lead in gasoline was mentioned, but lead from old water pipes, old methods of leather tanning (Cr), felt and gold processing (Hg), and old artisanal manufacture of metal alloys (Cu, Zn, Ni), etc., may leave a legacy of pollution in various soil layers. This is especially common in old urban areas where cycles of building, demolition, and rebuilding have occurred through centuries (see Figure 18.24).

Concentration in Living Tissues

Irrespective of their sources, people everywhere are exposed to these toxic elements every day, either through the air or through ingestion of food, water, and—yes—soil (see Box 18.2). Toxic metals can and do reach the soil by direct or indirect deposition, and from there they become part of the food chain: soil–plant–animal–human (Figure 18.25). Unfortunately, once the elements become part of this cycle, they may accumulate in animal and human body tissue to toxic levels.

This situation is especially critical for humans, fish, and other creatures at the top of the food chain. It has already resulted in restrictions on the use of certain fish and wildlife for human consumption. Because of the globalization of our food supply, crops grown on polluted soils in countries with weak environmental regulations (especially those with a recent history of "dirty" industrialization, such as China) may threaten the safety of food consumed in importing countries around the world. By the second decade of the twenty-first century it was clear that industrialization had severely contaminated soil in several parts of China to a degree

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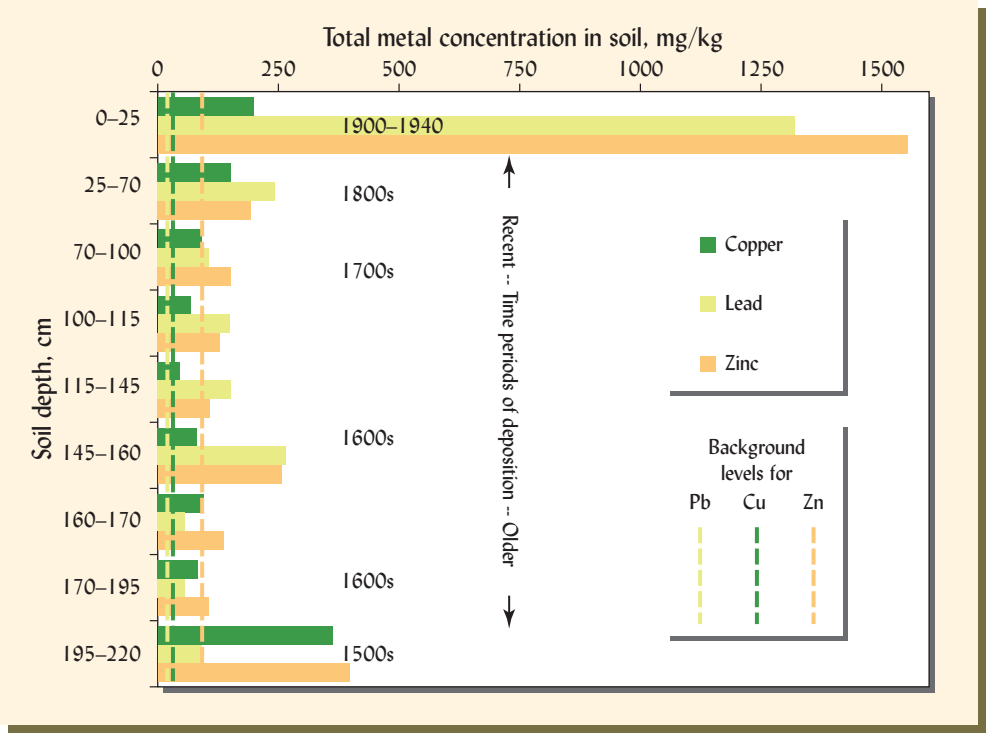

Figure 18.24 *History of copper, lead and zinc contamination of soils in central Moscow, Russia. The layers of contaminated urban soil go back to the founding of the city in the fourteenth century. The most serious contamination occurred during the industrialization of Russia following the Bolshevik revolution in the early twentieth century. However, the copper concentration is greatest in the oldest layers because of ancient artisanal metal working. Such legacy metal contamination exists in many older cities around the world.* [Graphed using data selected from Meuser (2010)]

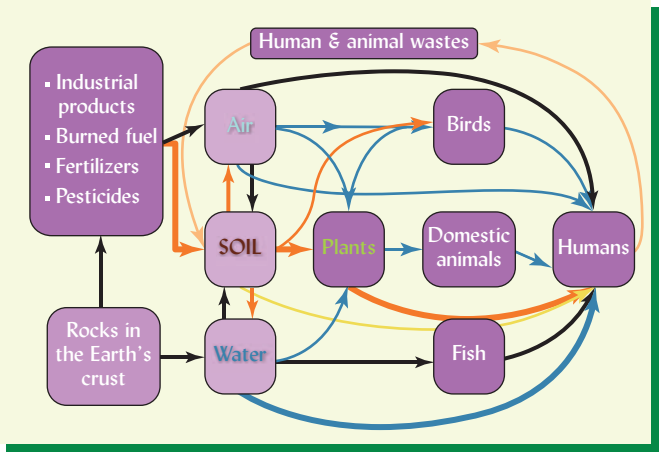

Figure 18.25 *Sources of heavy metals and their cycling in the soil–water–air–organism ecosystem, with an emphasis on human exposure. It should be noted that the content of metals in organism tissue generally builds up from left to right, indicating the vulnerability of humans (as secondary and tertiary food web consumers) to heavy metal toxicity. Note that air, water, and soil may also be directly ingested by humans.* (Diagram courtesy of Ray R. Weil)

that was affecting food safety. In China, urban agriculture is an important part of the fresh vegetable supply to cities, but unfortunately often uses derelict industrial land (brownfields) or land near major highways, industrial parks, solid waste disposal sites, petroleum processing facilities, mined land or mine spoils, and land irrigated with sewage (either treated or not). The main pollutants found in food from these farms were arsenic, cadmium, chromium, copper, lead, and mercury. Even basic grains are at risk. In a survey of some 160 thousand ha of rice fields in four heavily polluted regions and found that 2/3 or 110 thousand ha were severely polluted. Protection of the environment and food supplies requires that governments in all industrial nations take seriously the need to closely regulate the release of these toxic elements and the production of food in potentially contaminated soils.

Even in American suburban home gardens, where nearby industries are not a factor, there are possible sources of contamination, including the many outdoor decks,

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fences, and utility poles made from wood pressure-treated with chromated copper arsenate (CCA) as a preservative. Although no longer in use in the United States, most of the wood sold for outdoor use between 1975 and 2003 was treated with arsenic chemicals and remains a source of contamination. Leaching of arsenic (As) from the treated wood has been shown to contaminate the nearby soil and, in turn, the vegetables grown in it (Figure 18.28).

BOX 18.2

LEAD POISONING AND SOIL CONTAMINATION

Lead contamination is a serious and widespread form of inorganic soil pollution. Long-term exposure to low levels of lead can profoundly affect a child's development and neurological function, including intelligence. Lead poisoning has been shown to contribute to mental retardation, poor academic performance, and juvenile delinquency. In the past (and, unfortunately, in the present in many developing countries that still use leaded gasoline), much of the lead exposure came from burning leaded fuels. The content of lead in soils commonly increases with proximity to major highways. Inner city residents generally live surrounded by lead-contaminated soils. The soil on the windward side of apartment buildings often shows the highest accumulations of lead, as it is there that the wind-carried particulates tend to settle out of the air. A second reason for high lead concentrations in urban soils is related to the lead-based pigments in paint from pre-1970 era buildings. Paint chips, flakes, and dust from sanding painted surfaces spread the lead around, and eventually much of it ends up in the soil. During dry weather, soil particles blow about, spreading the lead and contributing to the dust that settles on floors and windowsills. Although plants do not readily take up lead through their roots, lead-contaminated dust may stick to foliage and fruits.

Eating these garden products and breathing in lead-contaminated dust are two pathways for human lead exposure (see Figure 18.25). However, the most serious pathway, at least for young children, is thought to be hand-to-mouth activity—basically, eating dirt (see also Box 1.1). Anyone who has observed a toddler knows that a child's hands are continually in its mouth (Figure 18.26). Lead-contaminated dust on surfaces in the home can therefore be an important source of lead exposure for young children; so, too, can lead-contaminated soil in outdoor play areas. Having children wash their hands frequently can significantly cut down their exposure to this insidious toxin. The U.S. EPA has set standards for the cleanup of lead in soil around homes: 400 mg of lead per kg dry soil in bare soil in children's play areas or 1200 mg/kg average for bare soil in the rest of the yard. Soils with lead levels higher than these standards require some remediation.

Since 1970, major government programs have aimed to reduce lead exposure from paint (lead paints are banned and existing lead paint must be removed or sealed), drinking water, and food (lead has been banned from solder used in pipe joints and food cans). As a result, median levels of lead in blood samples from U.S. children fell from 0.18 mg/L in 1970 to 0.03 mg/L in 1994. For children under age 6, blood levels above 0.10 mg Pb/L are considered elevated and a threat to health. Unfortunately, lead in soils has not been similarly addressed. The U.S. EPA reports that nearly 1 million children in America (especially in central cities) have dangerously elevated levels of lead in their blood. Not only are the children of poor, urban families more exposed to lead-contaminated soils than most, but their diets are typically lower in phosphorus and calcium, nutrients that could make them less susceptible to lead toxicity.

Figure 18.26 *Lead from car exhaust and old paint accumulates in urban soils, and hand-to-mouth activity is a major pathway for lead poisoning in young children.* (Photo courtesy of Ray R. Weil)

Current measures designed to protect children from lead in soil around the home include: (1) excavation and removal of the soil, (2) dilution by mixing in large amounts of noncontaminated soil, or (3) stabilization of the lead away from the reach of children and dust-creating winds. Excavation of soil around homes is extremely expensive and, given the low mobility of lead in soils, probably not necessary. Instead, the contaminated soil area may be covered with a thick layer of uncontaminated topsoil, a wooden deck, or pavement. Well-maintained turfgrass will prevent most dust formation and soil ingestion. Removal of lead-based paints is likewise very expensive and difficult, so isolating the lead-based paint under several coats of fresh paint can limit exposure.

(continued)

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BOX 18.2

LEAD POISONING AND SOIL CONTAMINATION *(CONTINUED)*

Effective phytoremediation techniques have not yet been developed to get the lead out of soils; however, leaving the lead in the soil but transforming it into a form that is not bioavailable might be just as good. Recent research (Figure 18.27) shows that phosphorus (fertilizer) can effectively transform bioavailable lead compounds into relatively inert, nonbioavailable forms. Orthophosphate ions (PO_4^{3-}) efficiently react with Pb in the soil solution to precipitate very insoluble minerals, mainly lead pyromorphite [$Pb_5(PO_4)_3OH$, Cl,F]. This approach was tested near Joplin in Missouri, USA, where a lead smelter had contaminated local soils from the 1880s to the 1960s, resulting in average Pb levels of 2400 mg Pb/kg. The soil was amended with phosphorus equal to 1% of the soil by weight (500–1000 times normal fertilization rates). After 32 months, P-treated and untreated soils were sampled and fed at several dose-rates to young pigs (whose digestive systems are similar to humans). Lead levels in the blood of pigs fed the phosphorus-treated soil were much lower than those fed the control soil (Figure 18.27), suggesting that although P-treatment leaves the lead in the soil, it could substantially reduce the hazard to children.

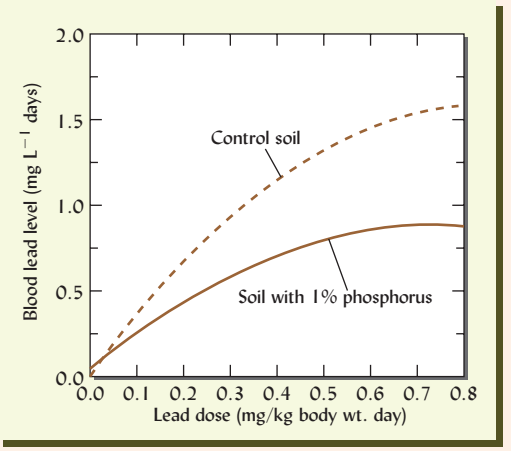

Figure 18.27 *In situ treatment of highly lead-contaminated soil with 1% P by weight substantially reduced the bioavailability of the lead, as evidenced by lower lead levels in the blood of pigs fed with the soil.* [Graphed from data in Ryan et al. (2004)]

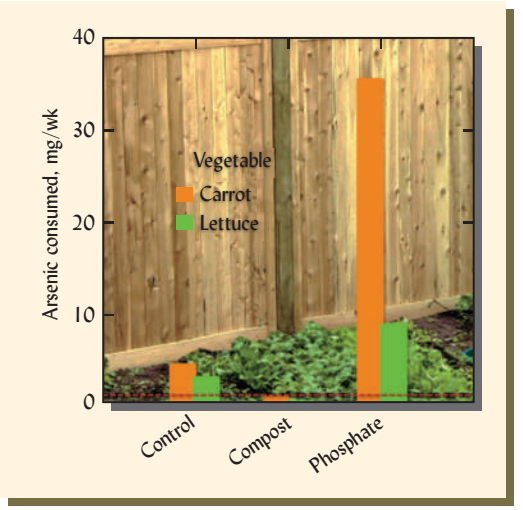

Figure 18.28 *Arsenic in a diet with carrots and lettuce grown in soil adjacent to wood fences and utility poles treated with chromated copper arsenate (CCA) as a wood preservative. Leaching of arsenic (As) from the treated wood contaminated the soil and, in turn, the vegetables grown in it. If a gardener ate the recommended daily servings of vegetables as lettuce and carrots from these gardens, the weekly As intake would be 3–4 times the provisional tolerable weekly intake (PTWI) for inorganic arsenic set at about 1 mg As per week (red dashed line). However, amending the soil with biosolids compost significantly reduced plant As compared to the untreated (control) soils. The As in water-soluble and exchangeable fractions in the soil was reduced, probably because of As adsorption by biosolids organic matter. However, adding phosphate fertilizer to this urban garden greatly increased the arsenic content of the carrots and lettuce grown. Arsenate (AsO_4^{3-}) is an oxyanion much like phosphate (PO_4^{3-}), rather than a metallic cation like lead (Pb^{+2}). Therefore, the phosphate replaced the sorbed arsenate. Thus, the effect on plant contaminant uptake of adding phosphate to soil was just the opposite for As as the effect shown for Pb in Figure 18.27.* [Graphed from tabular data in Cao and Ma (2004)]

Some Inorganic Contaminants and Their Reactions in Soils

Arsenic, as just mentioned, can leach from treated outdoor lumber. A broader problem is its accumulation in certain orchard soils following years of application of arsenic-containing pesticides. Being present in an anionic form (e.g., $H_2AsO_4^-$), this element is absorbed (as are phosphates) by hydrous iron and aluminum oxides, especially in acid soils. In spite of the capacity of most soils to tie up arsenates, long-term additions of arsenical sprays can lead to toxicities for sensitive plants and earthworms. The arsenic toxicity can be reduced by applications of sulfates of zinc, iron, and aluminum, which tie up the arsenic in insoluble forms. Toxicities from naturally occurring arsenic were discussed in Section 15.9.

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Lead contaminates primarily urban soils from vehicle exhaust and from old lead-pigmented paints (paint chips and dust from painted woodwork). However, other soils at shooting ranges, hunting grounds, and battlefields become contaminated with lead from bullets and buckshot. Most of the lead is tied up in the soil as low solubility carbonates, sulfides, and in combination with iron, aluminum, and manganese oxides (see Table 18.8). Consequently, the lead is largely unavailable to plants and not mobile enough to readily leach to groundwater. However, it can be absorbed by children who put contaminated soil or dust in their mouths (Box 18.2).

Mercury is released mainly from burning coal to generate electricity. When it contaminates lake sediments and wetlands, the result is toxic levels of mercury among certain species of fish. Insoluble forms of mercury in soils, not normally available to plants or, in turn, to animals, are converted by microorganisms to an organic form, methylmercury, which is more soluble and available for plant and animal absorption. The methylmercury is concentrated in fatty tissue as it moves up the food chain, until it accumulates in some fish to levels that may be toxic to humans. This series of transformations illustrates how reactions in soil can influence human toxicities.

Chromium in trace amounts is essential for human life, but, like arsenic, it is a carcinogen when absorbed in larger doses. This element is widely used in steel, alloys, and paint pigments. Chromium is found in two major oxidation states in upland soils: a trivalent form [Cr(III)], and a hexavalent form [Cr(VI)]. In contrast to most metals, the more highly oxidized state [Cr(VI)] is the more soluble, and its solubility increases above pH 5.5. This behavior is opposite that of Cr(III), which forms insoluble oxides and hydroxides above that pH level.

To remediate Cr(VI)-contaminated soil and water, it is useful to reduce the chromium to Cr(III) (see also Section 7.5). This reduction process is enhanced by anaerobic conditions [wet soil with an abundance of decomposable organic material to provide a large, biological oxygen demand (BOD)]. The organic matter serves as an electron donor and thereby hastens the

Table 18.8
HEAVY METALS IN SOIL THAT RECEIVED 870 MG/HA (DRY WEIGHT) OF "DIRTY" SEWAGE SLUDGE OVER TEN YEARS

The application rate far exceeded that required to supply nitrogen to the crops, suggesting the purpose was disposal rather than utilization. The sludge was incorporated into a Metea sandy loam (Typic Hapludalfs) in Michigan, USA, between 1977 and 1986, prior to source reduction programs to reduce the metal contents of most sewage sludges. The data are for Ap horizon samples taken four years after the last sludge application.

		Metal content, mg/kg					
Forms in soil	**Solubility**	**Cd**	**Cr**	**Cu**	**Pb**	**Ni**	**Zn**
Exchangeable and dissolved	Most	—	<1	4	<4	62	520
Acid soluble (carbonates, some organic)		3	38	140	19	170	1,940
Organic matter		<1	200	56	35	31	89
Fe and Mn oxides		<1	331	96	28	180	370
Residual (very insoluble sulfides, etc.)	Least	<1	48	11	99	24	56
Total of all forms		4.5	617	307	181	467	2,975
Totals		Metal content, kg/ha[a]					
Total measured in Ap horizon		12	1,728	859	507	1,308	8,330
Total content in sludge applied		21	3,000	1,800	480	2,100	11,300
Apparent recovery, %		60	58	48	106	62	74

[a]Conversion from mg/kg to kg/ha assumes bulk density = 1.4 Mg/m^3 and sampling depth = 20 cm. *The CEC was 7 cmolc/kg, organic matter was 7%, and pH was 6.9.* Metal concentration data from Berti and Jacobs (1996). See also McBride et al. (1999) for further evidence of sludge-borne metal mobility in soils.

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reduction of Cr(VI) to the trivalent state [Cr(III)]. Provided the pH is maintained above 5.5, chromium in this reduced state will remain relatively stable, immobile, and nontoxic.

Boron can contaminate soil via high-boron irrigation water, by excessive fertilizer application, or by the use of power plant fly ash as a soil amendment. Boron may be adsorbed by organic matter and clays but may still be available to plants, except at high soil pH. Boron is relatively soluble in soils, toxic quantities being leachable, especially from acid sandy soils. Boron toxicity in plants is usually a localized problem and is probably much less important than boron deficiency (see Section 15.9).

Fluorine toxicity is also generally localized. Drinking water for animals and fluoride fumes from industrial processes often contain toxic amounts of fluorine. The fumes can be ingested directly by animals or deposited on nearby plants. If the fluorides are adsorbed by the soil, their uptake by plants is restricted. The fluorides formed in soils are highly insoluble, the solubility being least if the soil has a pH above neutral and high calcium saturation.

Selenium, which derives mainly from certain soil parent material, can accumulate in soils and plants to toxic levels, especially in arid regions (see Section 15.9 and Box 15.2 for details).

18.7 POTENTIAL HAZARDS OF CHEMICALS IN SEWAGE SLUDGE

The domestic and industrial sewage sludges considered as nutrient sources in Chapter 16 can be important sources of potentially toxic chemicals. About half of the municipal sewage sludge produced in the United States and in some European countries ends up applied to soils, either on agricultural land or to remediate land disturbed by mining and industrial activities (Figure 18.29). Industrial sludges—or municipal sewage sludges from systems that treat both industrial and human wastes—commonly carry significant quantities of inorganic as well as organic chemicals that can have harmful environmental or human health effects. The sludge contaminants that have received the most attention are the heavy metals.

Heavy Metals in Sewage Sludge

Concern over the possible buildup of heavy metals in soils resulting from large land applications of sewage sludges has prompted research on the fate of these chemicals in soils. Most attention has been given to zinc, copper, nickel, cadmium, and lead, which are commonly present in significant levels in these sludges. Many studies have suggested that if only moderate amounts of sludge are added, and the soil is not very acid (pH > 6.5), these elements are generally bound by soil constituents; they do not then easily leach from the soil, nor are they readily available to plants. Only in moderately to strongly acid soils have most studies shown significant movement down the profile from the layer of application of the sludge. Monitoring soil acidity and using judicious applications of lime have been widely recommended to prevent leaching into groundwater and minimize uptake by plants.

Other studies using large amounts of sludge (up to and exceeding what is permitted by U.S. EPA regulations) have suggested that metals from sludge may initially be more

Figure 18.29 *Sewage sludge slurry being transferred from a tanker truck to a floatation tire spreader for injection into soils during an ecological restoration project on orphan mined land. Such sludge applications are closely regulated on the basis of allowable metal levels in soil and sludge.*
(Photo courtesy of Ray R. Weil)

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mobile in soils than was previously thought. In fact, several studies have reported that from 20–80% of the metals applied with sludge at high rates have been leached from the root zone and, in all likelihood, were lost to the groundwater. The metals in these studies probably moved as soluble organic complexes while the sludge-soil mixture was still fresh. Over time, the metals remaining in the soil appear to be stabilized in various low-solubility soil fractions (Table 18.8).

Forms Found in Soils Treated with Sludge. By using a sequence of chemical extractants, researchers have found that heavy metals are associated with soil solids in four major ways (Table 18.8). First, a very small proportion is held in *soluble* or *exchangeable forms*, which are available for plant uptake. Second, the elements are bound by the *soil organic matter* and by the *organic materials* in the sludge. High proportions of copper and chromium are commonly found in this form, while lead is not so highly attracted. Organically bound elements are not readily available to plants, but may be released over a period of time.

The third and fourth forms of heavy metals in soils are associations with *carbonates* and with *oxides of iron and manganese.* These forms are less available to plants than either the exchangeable or the organically bound forms, especially if the soils are not allowed to become too acid. The fifth association is commonly known as the *residual form*, which consists of sulfides and other very insoluble compounds that are less available to plants than any of the other forms.

It is fortunate that most soil-applied heavy metals are not readily absorbed by plants and that they are not easily leached from the soil. However, the immobility of the metals means that they will accumulate in soils if repeated sludge applications are made. Care must be taken not to add such large quantities that the capacity of the soil to react with a given element is exceeded. It is for this reason that regulations set maximum cumulative loading limits for each metal (see Table 18.10).

Source Reduction Programs. A great deal was learned during the 1970s and 1980s about the contents, behavior, and toxicity of metals in municipal sewage sludges. As a result of the research, source reduction programs were implemented in the United States and elsewhere, which required industries to clean pollutants out of their wastewater *before* sending it to municipal wastewater treatment plants. In many cases, the recovery of valuable metal pollutants was actually profitable for industries. Because of these programs, municipal sewage sludges are much cleaner than in the past (Table 18.9). Note that the median levels of the most toxic industrial pollutants (Cd, Cr, Pb, and PCB) declined dramatically between the 1976 survey and the 1990 survey. Since much of the copper comes from the plumbing in homes (metallic copper is slightly solubilized in areas with acidic water supplies), that metal has been less affected by the source reduction regulations.

Regulation of Sludge Application to Land. The lower levels of metals (and of organic pollutants) make municipal sewage sludges much more suitable for application to soils than in the past, at least in countries where this issue is effectively regulated. Today, the amount of sludge that can be applied to agricultural land is more often limited by the potential for nitrate pollution from the nitrogen or phosphorus it contains, rather than by the metal content of the sludge. Nonetheless, application of sewage sludge to farmland is closely regulated to ensure that the metal concentrations in the sludge do not exceed the standards and that the total amount of metal applied to the soil over the years does not exceed the regulatory maximum accumulative loading limit. The fact that metal-loading standards differ considerably between countries (see Table 18.10) is an indication that the nature of the metal contamination threat is still somewhat uncertain and controversial.

Toxic Effects from Sludge. The uncertainties as to the nature of many of the organic chemicals found in the sludge, as well as the cumulative nature of the metals problem, dictate continued caution in the regulations governing application of sludge to croplands. The effect of application of a high-metal sludge on heavy metal content of soils and of earthworms living in the soil is illustrated in Table 18.11. The sludge-treated soils, as

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Table 18.9
MEDIAN POLLUTANT CONCENTRATIONS IN SEWAGE SLUDGES IN THE UNITED STATES IN 1976 AND 1990 AND IN UNCONTAMINATED AGRICULTURAL SOILS AND COW MANURE

	Concentration, mg/kg dry weight			
Pollutant	Sludges surveyed in 1990[a]	Sludges surveyed in 1976	Agricultural soils	Typical values for cow manure
As	6	10	5.2	4
Cd	7	260	0.20	1
Cr	40	890	37	56
Cu	463	850	18.5	62
Hg	4	5	0.06	0.2
Mo	11	—	—	14
Ni	29	82	18.2	29
Pb	106	500	11.0	16
Zn	725	1740	53.0	71
PCB	0.21	9	—	0

[a]For 1990 from Chaney (1990); for 1976 from Sommers (1977) except PCB value is median of cities in New York from Furr et al. (1976); for soils, median of 3045 surface soils from Holmgren et al. (1993).

Table 18.10
REGULATORY LIMITS ON INORGANIC POLLUTANTS (HEAVY METALS) IN SEWAGE SLUDGE APPLIED TO AGRICULTURAL LAND

			Cumulative allowable pollutant loading, kg/ha		
Element	Maximum concentration in sludge, USEPA,[a] mg/kg	Annual pollutant loading rates, USEPA, kg/ha/yr	USEPA	Germany	Ontario, Canada
As	75	2.0	41	—	28
Cd	85	1.9	39	3.2	3.2
Cr	3000	150.0	3000	200	240
Cu	4300	75.0	1500	120	200
Hg	57	0.85	17	2	1.0
Mo	75	—	—	—	8
Ni	420	21	420	100	64
Pb	840	15	300	200	120
Se	100	5.0	100	—	3.2
Zn	7500	140	2800	400	440

[a]U.S. EPA (1993).

well as the bodies of earthworms living in these soils, were much higher in cadmium and zinc than was the case in soils where sludge had not been applied. One would expect further concentration to take place in the tissue of birds and fish that might consume the earthworms.

Farmers must be assured that the levels of inorganic chemicals in sludge are not toxic to plants (a possibility mainly for zinc and copper) or to humans and other animals who consume

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Table 18.11
HEAVY METALS IN SOIL AND IN EARTHWORMS AS INFLUENCED BY SEW AGE SLUDGE
Note the high concentration of cadmium and zinc in the earthworms.

	Concentration of metal, mg/kg			
	Soil		Earthworms	
Metal	Control	Sludge-treated	Control	Sludge-treated
Cd	0.1	2.7	4.8	57
Zn	56	132	228	452
Cu	12	39	13	31
Ni	14	19	14	14
Pb	22	31	17	20

From Beyer et al. (1982).

Table 18.12
METAL UPTAKE BY CORN AFTER 19 YEARS OF FERTILIZING WITH LIME-STABILIZED SEWAGE SLUDGE
As is typical, metals accumulated less in grain than in leaves and stalks (stover). The annual sludge rate of about 10.5 Mg was designed to supply the nitrogen needs of the corn. The sludge had little effect on the metal content of the plants, except in the case of zinc (which increased, but not beyond the normal range for corn).

	Zn	Cu	Cd	Pb	Ni	Cr
Cumulative metal applied in sludge, kg/ha	175	135	1.2	49	4.9	1045
Treatment	*Uptake in stover, mg/kg*					
Fertilizer	18	8.4	0.16	0.9	0.7	0.9
Sludge	46.5	7.0	0.18	0.8	0.6	1.4
	Uptake in grain, mg/kg					
Fertilizer	20	3.2	0.29	0.4	0.4	0.2
Sludge	26	3.2	0.31	0.5	0.3	0.2

Data for Typic Hapludolls in Minnesota abstracted from Dowdy et al. (1994).

the plants (a serious consideration for As, Cd, Cr, and Pb). For relatively low-metal municipal sludges, application at rates just high enough to supply needed nitrogen seems to be quite safe (Table 18.12).

Direct ingestion of soils and sludge is also an important pathway for human and animal exposure. Animals should not be allowed to graze on sludge-treated pastures until rain or irrigation has washed the sludge from the forage. Children may eat soil while they play, and a considerable amount of soil eventually becomes dust in many households. Direct ingestion of soil and dust is particularly important in lead toxicity.

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18.8 PREVENTION AND REMEDIATION OF INORGANIC SOIL CONTAMINATION[6]

Three primary methods of alleviating soil contamination by toxic inorganic compounds are: (1) to eliminate or drastically reduce the amounts of toxin applied to or allowed to reach the soil; (2) to immobilize the toxin by means of soil management, to prevent it from moving into food or water supplies; and (3) in the case of severe contamination, to remove the toxin from the soil by chemical, physical, or biological remediation.

Reducing Soil Application

The first method requires action to reduce unintentional contamination from industrial operations and from automobile, truck, and bus exhausts. Decision makers must recognize the soil as an important natural resource that can be seriously damaged if its contamination by unintended addition of inorganic toxins is not curtailed. One of the considerations in life cycle sustainability analysis should be the likelihood of soil contamination. For example, during their lifetimes, cars and trucks emit contaminants, not only in their exhaust fumes, but also from brake linings (copper) and tire wear (cadmium, zinc)—all of which can wash off paved roads onto soils. Potential contamination issues from the improper disposal of discarded electronics are of increasing concern (tin, lead, beryllium cadmium, mercury). Also, there must be judicious reductions in *intended* applications to soil of the toxins through pesticides (arsenic, copper), fertilizers (cadmium, zinc), irrigation water (selenium, boron), and composted solid wastes.

Immobilizing the Toxins

Soil and plant management can help reduce the continued cycling of these inorganic chemicals by stimulating changes that keep the chemicals in the soil rather than encouraging their uptake by plants or leaching by drainage water. By immobilizing and becoming a sink for the toxins, the soil breaks the soil–plant–animal (humans) cycle through which the toxin exerts its effect. For example, most of these elements are rendered less mobile and less available if the pH is kept near neutral or above. Liming of acid soils reduces metal mobility; hence, regulations require that the pH of sludge-treated land be maintained at 6.5 or higher. However, it is important to know which contaminants are present as certain toxic elements, such as arsenic and molybdenum, have the opposite response to pH change and become more soluble and bio-available at high pH levels.

Draining wet soils can be beneficial, since the oxidized forms of the several toxic elements are generally less soluble and less available for plant uptake than are the reduced forms. However, again, there are exceptions and the opposite is true for chromium. The oxidized Cr(VI) is mobile and highly toxic to humans (see Section 18.8).

Heavy phosphate applications may reduce the availability of metal cations such as lead that react with P to form insoluble compounds (see Box 18.2). However, again, the opposite effect may be realized, for example, with arsenic, which is found in the anionic form and is desorbed by phosphate (see Figure 18.28). Leaching may be effective in removing excess boron, although moving the toxin from the soil to water is not likely be of real benefit.

Application of organic matter, especially heavy applications of compost, generally reduces the mobility and bioavailability of many of the inorganic toxins. The stabilized organic matter seems to strongly adsorb many elements, preventing their bioconcentration in plants. That is, plants species differ in their ability to take up metals such that the contaminant may be many times more or many time less concentrated in the plant tissue than in the soil from which it was taken up.

$$\text{Bioconcentration factor, BCF} = \frac{\text{mg/kg, plant}}{\text{mg/kg, soil}} \tag{18.4}$$

[6]For phytoremediation of a large area of soils in Thailand too contaminated with Cd and Ni to produce rice for human consumption, see Simmons et al. (2014). For reviews of plant accumulation of metals from soils and the use of natural organic materials to enhance this process, see van der Ent et al. (2013) and Wiszniewska et al. (2016).

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Plants with a relatively high bioconcentration factor (BCF) are likely to be more toxic to consuming organisms further up the food chain than plants with lower BCF values. For example, on contaminated urban gardens in one study (Figure 18.30) the bioconcentration factor was much higher for lead than for arsenic and about ten times as great for carrot as for lettuce or tomato. Amending the soil with very large amounts of biosolids and sawdust based compost reduced the BCF by a modest but significant degree in most cases.

Care should be taken in selecting food plants to be grown on metal-contaminated soil. Generally, plants translocate much larger quantities of metals to their leaves than to their fruits or seeds (see Table 18.12). Root vegetables can also be problematic. Fruits or grains only rarely accumulate high concentration of metals. The greatest risk for food-chain contamination with metals is therefore through leafy vegetables, such as lettuce and spinach, or through forage crops eaten by livestock. On the other hand, nonfood plants with a high propensity to take up metals from contaminated soil can be put to good use for remediation.

Bioremediation by Metal Hyperaccumulating Plants

As just discussed, different plant species are characterized by wide propensities to take up metals from soil. Plants also differ widely in their responses to the accumulation of high concentrations of metals in their roots—some die, some survive by sequestering the metal in their root tissue, while others thrive and translocate the metal to their shoots. Based on these characteristics, plants can be grouped into four categories: sensitive plants, indicator plants, excluder plants, or hyperaccumulator plants (Figure 18.31).

Sensitive plants tend to take up metals readily but then cannot tolerate the resulting high metal concentrations in their tissues. They become poisoned by the metals, their growth is inhibited, and they are likely to die if grown in even moderately metal-contaminated soils. With regard to most heavy metals, the majority of plants fall into this category.

Indicator plants steadily take up the metal in proportion to how much is available in the soil. This trait makes them useful as indicators of soil metal concentrations. They survive from very low to quite high soil metal concentrations, but they do not accumulate concentrations of the metal in their tissues that exceed the concentrations in the soil. They manage to tolerate moderately high levels of metal taken up by sequestering the metal nonsensitive plant parts or by binding the metals in organic compounds that reduce the toxicity.

Excluder plants can tolerate quite high levels of metal contamination, but they do so by either excluding the metal and avoiding its uptake, or by isolating the metal in the root and not translocating it to the shoot. That is, excluder plants may exhibit a high bioconcentration factor in the root ($BCF_{root} > 1$), but not in the shoot ($BCF_{shoot} = 1$). This behavior may be useful in stabilizing the metal in the soil, but does not facilitate the removal of the metal altogether.

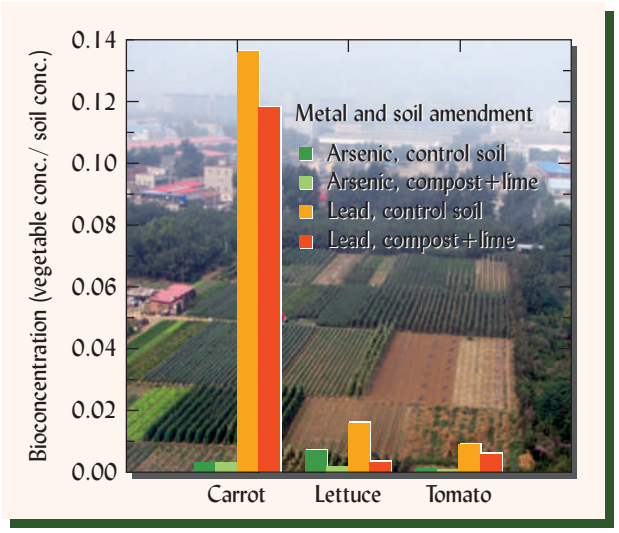

Figure 18.30 *Bioconcentration factors in three vegetable crops grown in urban lots with soil contaminated by both arsenic and lead. All three species excluded the contaminants to some extent, but for Pb carrot was much less exclusionary than the others. The soil in some plots was amended with 180 Mg/ha of biosolids + 180 Mg/ha of a sawdust/sand/lime mixture. This amendment significantly reduced the BCF for As in lettuce and for Pb in carrot and lettuce. The soil pH ranged from 5.6 to 5.9 and contained 200–300 mg/kg Pb.* [Means for two years graphed from tabular data in Defoe et al. (2014), background photo of other urban vegetable farms near Beijing, China, courtesy of Ray R. Weil]

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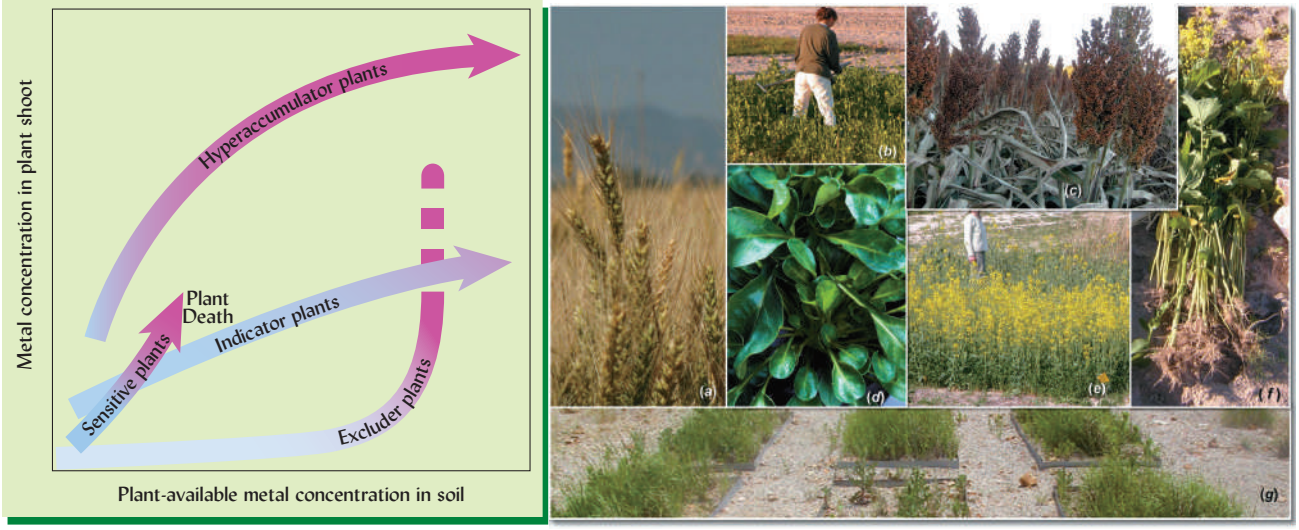

Figure 18.31 *Plant responses to metal contamination in soils fall into four categories. Sensitive plants accumulate metals but cannot tolerate high levels. Indicator plants and excluder plants may be useful for bioremediation by phytostabilization. Hyperaccumulator plants present the most potential for bioremediation by phytoextraction. Examples of the wide range of crop and noncrop plants that show potential for phytoremediation: (a) wheat acts as an excluder plant for Ni; (b) collecting soil samples in a mixed stand of Brassicas; (c) sorghum accumulates high levels of Pb; (d)* Thlapsi *spp. hyperaccumulate Zn and Cd; (e) research plots with mustards; (f) roots and shoots of mustard plant that hyperaccumulate several metals; (g) research plots testing heavy compost application to bind toxic metals at a zinc mine site.* [Photo (g) courtesy USDA/Agric. Research Service; other photos courtesy of Ray R. Weil; diagram redrawn with concepts from van der Ent et al. (2013)]

To be useful in remediating metal contaminated soils by *phytoextraction*, a plant must not only take up large amounts of the metal, but must also translocate the metal to the above ground plant parts for practical metal removal with plant harvest. This is where hyperaccumulating plants come into the story. **Hyperaccumulator plants** not only tolerate extremely high metal concentrations in soils, they also efficiently extract the metal from the soil, translocate the metal to aboveground parts from their roots, and continue to grow unimpaired with extremely high metal concentrations in their shoot tissues. Researchers have found most known hyperaccumulator species among plants growing and evolving naturally in old polluted sites or soils naturally high in metals (such as serpentine-derived soils, see Section 15.2). Hundreds of hyperaccumulating plant species from dozens of plant families have been identified, but the Cruciferae, including the genera Brassica, Alyssum, and Thlaspi, stand out as supplying many hyperaccumulators.

Hyperaccumulator plants may accumulate more than 20,000 mg/kg nickel, 40,000 mg/kg zinc, and 1000 mg/kg cadmium. While such plants would pose a serious health hazard if eaten by animals or people, they may offer one of the most practical and sustainable solutions for the remediation of large, extensive, or environmentally sensitive areas with metal-contaminated soils. With concentrations of 2–4% metal (e.g., Ni or Zn), the plant tissue is so concentrated that it could be used as an "ore" for smelting new metal. Since the total amount of metal removed is the product of tissue concentration (mg/kg) and dry matter production (kg/ha), it is not enough to find plants that accumulate 10,000–50,000 mg/kg metal in their dry matter (1–5000 if the most highly toxic metals like Cd are considered). Up to now, the main limitation of the practicality of the phytoextraction process is the rather puny growth rates and dry matter production of most hyperaccumulating plants. For example, a recent project used *Thlaspi caerulescens* to phytoremediate Cd and Ni contaminated rice fields in Thailand and applied best management practices to promote high metal availability (lowered pH) and high plant growth (N, P , Zn fertilizers, fungicides to control disease, high population density), but it was estimated that it would still take about 60–80 harvests of 30–40 years to lower the Cd content of the soil from 10 down to an acceptable 3 mg/kg.

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Management to Enhance Phytoremediation

In addition to manipulating soil pH and redox conditions, as already mentioned, organic materials, composts and biochars of various kinds are being experimented with to enhance phytoremediation. One way these material increase plant metal uptake is by chelation. The natural materials or synthetic chelating agents can be applied to soils to enhance the removal of lead and other metals by phytoremediation. Lead in soils is strongly bound by both mineral and organic colloids and is thus only very sparingly available to plants. In a form of enhanced rhizosphere bioremediation, added chelates solubilize the lead, and plants such as Indian mustard are used to remove it.

Encouraging an active soil faunal community may also play a role. Earthworms have been found to make lead more easily taken up by plants and leached from soils during bioremediation effort (Table 18.13).

Genetic and bioengineering techniques are being applied to develop high-yielding hyperaccumulating plants that can remove larger quantities of heavy metal contaminants from soils. For example, wide genetic variation in heavy metal accumulation by different strains of Alpine pennycress suggests the potential for breeding improved accumulating plants. Also, research to insert genes responsible for contaminant accumulation into other higher-yielding plants, such as canola and Indian mustard, is being explored.

18.9 LANDFILLS[7]

A visit to the local landfill would convince anyone of the wastefulness of modern societies. And the problem is only getting worse by the day. Estimates are that 1.4 billion Mg of solid waste is generated annually and current trends suggest this amount may double before 2030. Costs for dealing with all this waste are estimated at well over $200 billion per year. In the United States, which is now second to China as the greatest waste generating country, people generate about 260 million Mg of municipal wastes each year (Figure 18.32).

The Municipal Solid Waste Problem

Most (about 70%) municipal solid waste material is organic in nature, largely paper, cardboard, and food or yard wastes (e.g., grass clippings, leaves, and tree prunings). The other

Table 18.13
EARTHWORMS' EFFECTS ON THE MOBILITY OF COPPER, ZINC, LEAD, AND ARSENIC IN CONTAMINATED SOIL
Incubating soil with earthworms (Lumbricus terrestris) *for 112 days increased both plant uptake and leaching.*

	Concentration in rye plant tissue				Concentration dissolved in leachate					
	Cu	Zn	Pb	As	Cu	Zn	Pb	As	pH	DOC
	mg kg^{-1}				μg L^{-1}					mg L^{-1}
No earthworms	36	120	2.9	4.7	3.0	128	1.0	0.6	4.1	4.2
L. terrestris	48*	140*	3.5	12*	12.0*	549*	1.9*	1.6*	3.7*	3.9

*Asterisk indicates values that differ statistically between the soils that were incubated with or without earthworms.
Data selected from Sizmur et al. (2011).
Soil was collected (0–30 cm) from a grassed field—a former settling pond for the separation of metal from crushed ores at an abandoned copper and arsenic mine near Gunnislake, UK.

[7]For details on the soil and geotechnical aspects of landfill design, see Qian et al. (2002) and settlement and other limitation for use after landfill closure, see Wong et al. (2013).

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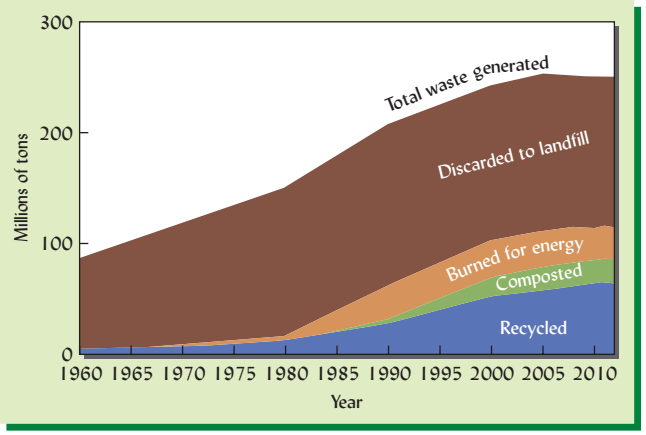

Figure 18.32 *Historical and predicted trends in municipal solid-waste management in the United States. Soils play a central role in the composting and landfilling options.* [Diagram courtesy of Ray R. Weil; Data from U.S. EPA (2014)]

30% consists mainly of such nonbiodegradables as glass, metals, and plastics. Environmentally speaking, the good news is that since 2000 total waste generation in the United States has not increased (it had doubled between 1965 and 1995) and the per capita generation has actually declined. Since the overall economy has grown during that period, the data indicate that the United States has been successful in decoupling waste generation from economic growth. Environmental education and municipal recycling programs have paid off with an ever-increasing proportion of wastes being recycled, composted, or burned for energy recovery (Figure 18.32). Still, the present reality is that at least half of municipal solid wastes are buried in the ground (landfilled) and will probably continue to be disposed of in this manner for some time to come. In lesser developed countries wastes may not even be properly buried, but instead simply either dumped at the city's edge or, where municipal collection is inadequate, left to pile up in the streets, alleys, and riverbanks (Figure 18.33) where they sadly degrade the livability of the cities and release toxins and pathogens to the environment. For the poor in some of these cities, the exposed wastes represent a means of making a living by picking through the trash and selling the most valuable and easily recovered waste materials for metal recovery and recycling.

Regardless of location, it is important to understand that the entire waste disposal problem could be greatly reduced by creating less waste in the first place — implementing policies of "reduce and reuse." Second, it is possible to eliminate most problems associated with waste disposal by two simple measures: (1) keeping the metals, glass, plastics, and paper separate for easy recycling (Figure 18.33, *left*), and (2) composting the yard wastes, food wastes, and some of the paper products. Composting can be done on-site by home owners and waste generators, or by municipalities using collected organic wastes (Section 12.11). The composted product from a number of municipalities is successfully used as a beneficial soil amendment (see Section 16.5). The small fraction of more hazardous wastes remaining can then be detoxified or concentrated and reused or immobilized.

Figure 18.33 *Alternatives to burying wastes in the soil.* (Left) *Vending machines in reverse: residents of New York City, USA, bring collected wastes to be deposited in "vending" machines that pay out cash in return.* (Right) *Residents of a small West African city go about their business amidst sea of uncollected solid wastes.* (Photos courtesy of Ray R. Weil)

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In the past, wastes were merely placed in open "dumps" and, often, set afire. The term *landfill* came into use because wastes were often dumped into gullies, ravines, or swampy lowland areas where, eventually, their accumulation filled in the lowland, creating areas for urban parks and other facilities. Locating landfills on wetlands is no longer an acceptable practice.

Two Basic Types of Landfill Design

Although landfill designs vary with the characteristics of both the site and the wastes, two basic types of landfills can be distinguished: (1) the natural attenuation or unsecured landfill, and (2) the containment or secured landfill. We will briefly discuss the main features of each.

Natural Attenuation Landfills

The purpose of a natural attenuation landfill is to contain nonhazardous municipal wastes in a sanitary manner, protect them from animals and wind dispersal, and, finally, to cover them sufficiently to allow revegetation and possible reuse of the site. Although the landfill is engineered to reduce water infiltration, some rainwater is allowed to percolate through the waste and down to the groundwater (Figure 18.34). Natural processes are relied upon to attenuate the leachate contaminants before the leachate reaches the groundwater. Soils play a major role in these natural attenuation processes through physical filtering, adsorption, biodegradation, and chemical precipitation (Table 18.14).

Soil Requirements. Finding a site with suitable soil characteristics is critical for a natural attenuation landfill. There must be at least 1.5 m of soil material between the bottom of the landfill and the highest groundwater level. This layer of soil should be only moderately permeable. If too permeable (sandy, gravelly, or highly structured), it will allow the leachate to pass through so quickly that little attenuation of contaminants will take place. The soil must have sufficient cation exchange capacity to adsorb NH_4^+, K^+, Na^+, Cd^{2+}, Ni^{2+}, and other cations that the wastes are expected to release. The soil should also adsorb and retard organic contaminants long enough

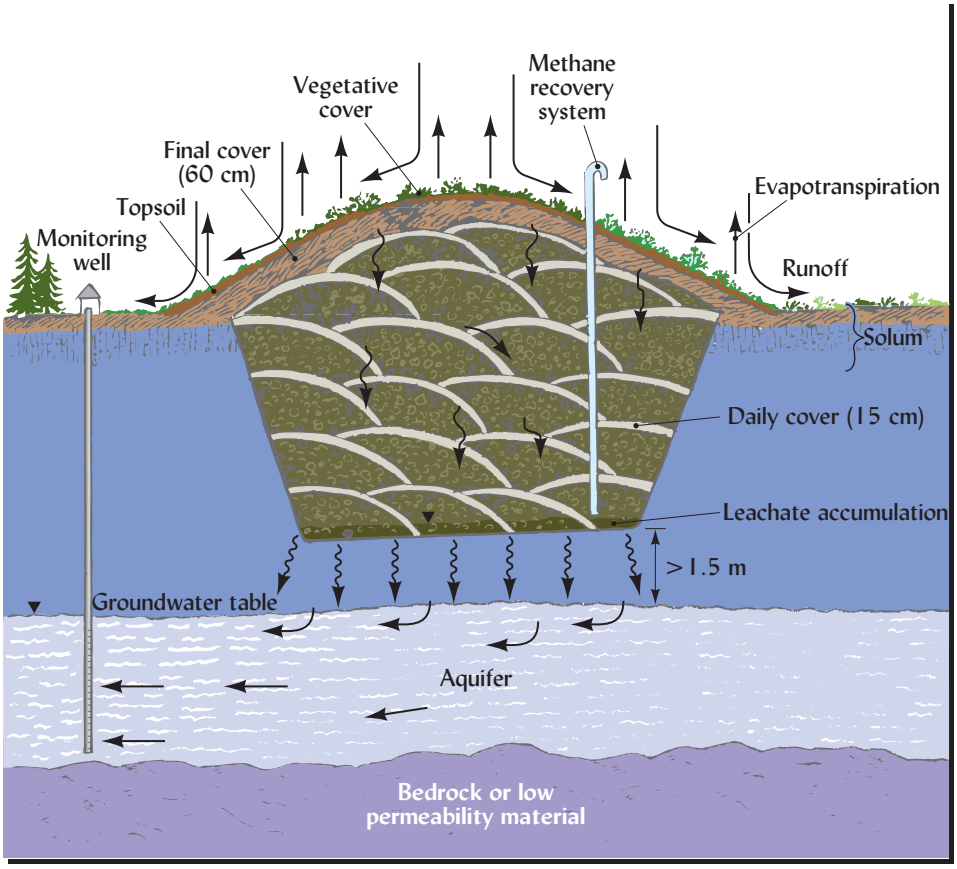

Figure 18.34 *A natural attenuation landfill depends largely on soil processes to attenuate the contaminants in the leachate before they reach the groundwater. Compare to the containment landfill design illustrated in Figure 18.38.* (Diagram courtesy of Ray R. Weil)

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Table 18.14
SOME ORGANIC AND INORGANIC CONTAMINANTS IN UNTREATED LEACHATE FROM MUNICIPAL LANDFILLS
Range of concentrations and typical sources of the contaminants and mechanisms by which soils can attenuate the contaminants are also given. The ranges show that leachates vary greatly among landfills.

Chemical	Concentration, μg/L	Common sources	Mechanisms of attenuation
		Organics	
Dissolved organic matter,	140,000 –	Rotting yard wastes, paper, and garbage	Biological degradation
Dissolved organic matter as chemical oxygen demand (COD)	140,000–150,000,000	Rotting yard wastes, paper, garbage	Biological degradation
Benzene	0.2–1,630	Adhesives, deodorants, oven cleaner, solvents, paint thinner, and medicines	Filtration, biodegradation, and methanogenesis
Trans 1,2-dichloroethane	1.6–6,500	Adhesives and degreasers	Biodegradation and dilution
Toluene	1–12,300	Glues, paint cleaners and strippers, adhesives, paints, shampoo, and carburetor cleaners	Biodegradation and dilution
Xylene	0.8–3,500	Oil and fuel additives, paints, and carburetor cleaners	Biodegradation and dilution
		Metals	
Nickel	15–1,300	Batteries, electrodes, and spark plugs	Adsorption and precipitation
Chromium	20–1,500	Cleaners, paint, linoleum, and batteries	Precipitation, adsorption, and exchange
Cadmium	0.1–40	Paint, batteries, and plastics	Precipitation and adsorption

Leachate concentration ranges from a review of hundreds of landfills built since 1965, in Kjeldsen et al. (2002).

to allow a high degree of microbial degradation. On the other hand, if the soil is too impermeable, the leachate will build up, flood the landfill, and seep out laterally.

Daily and Final Soil Cover. The site for a natural attenuation landfill should also provide soils suitable for daily and final cover materials. At the end of every workday, the waste must be covered by a layer of relatively impermeable soil material (Figure 18.35). The daily cover prevents blowing waste and odors escaping and excludes vermin to some extent.

The final cover for the landfill is much thicker than the daily covers, and includes a 60- to 100-cm-thick layer of low-permeability, clay soil material designed to minimize percolation of water into the landfill. This impermeable layer of compacted clay is usually then covered with a 30- to 45-cm layer of highly permeable medium to coarse sand. This sand layer is designed to allow water to drain laterally off the landfill to a collection area.

On top of the sand, a thinner layer of loamy "topsoil" is installed. The moderately permeable topsoil layer is meant to support a vigorous plant cover that will prevent erosion and use up water by evapotranspiration. The whole system is designed to limit the amount of water percolating through the waste, so that the amounts of contaminated leachate generated will not overwhelm the attenuating capacity of the soil between the landfill bottom and the groundwater (Figure 18.36).

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Figure 18.35 *A bulldozer compacts and buries trash in an old natural attenuation landfill in deep, well-drained soils. The trash is covered daily by 15 cm of soil to prevent it from being carried away by wind or infested with rats. Once the entire trench is filled, a much thicker final cover of soil will be applied. Note the lack of any geomembrane liner or leachate collection system in this landfill.* (Photo by Ray R. Weil)

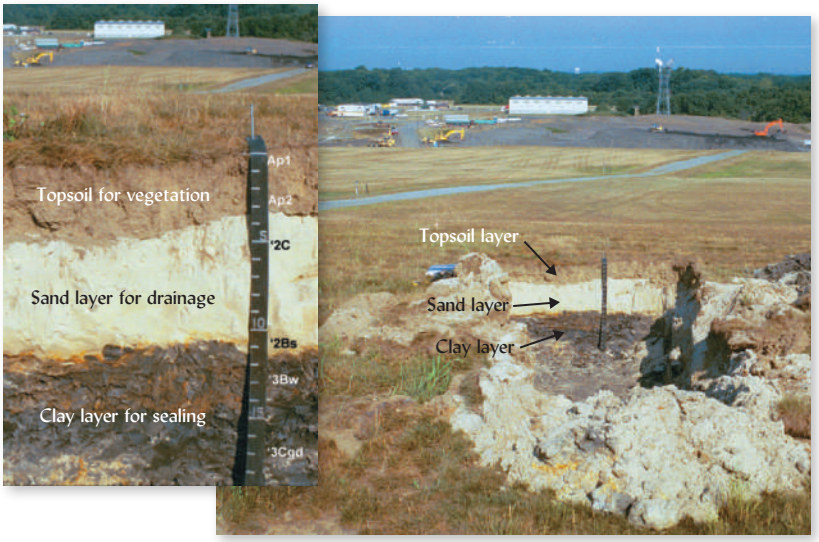

Figure 18.36 *An observation pit dug in an engineered soil used to cap a completed section of a landfill in New Jersey, USA. The pit excavation has revealed the three basic layers of the landfill cap. A compacted clay layer serves to seal the underlying garbage and prevent infiltration of water so as to minimize the formation of landfill leachate. A layer of loose, clean, medium sand was installed above the clay to serve as a drainage layer, which guides water horizontally over the clay and off the landfill cell to a collection pond (not shown). On top of the sand, a layer of sandy loam topsoil was installed from Ap horizon material hauled in from a distant site. The topsoil serves as growing medium for the grassy vegetative cover that protects and stabilizes the landfill cap. This pit, dug six years after the landfill cap was placed, shows signs of in situ soil development and acid sulfate weathering (2Bs horizon) from the unfortunate use of high sulfide clay.* (Photos courtesy of Chris Smith, USDA/NRCS)

Containment or Secured Landfills

The second main type of landfill is much more complex and expensive to construct, but its construction and function is much less dependent on the nature of the soils at the site. The design (see Figure 18.37) is intended to contain, pump, and treat all leachate from the landfill, rather than to depend on soil processes for cleansing the leachate on its way to the groundwater. To accomplish the containment, one or more impermeable liners are set in place around the sides and bottom of the landfill. These are often made of expanding clays (e.g., bentonite) that swell to a very low permeability when wet. Plastic, watertight geomembranes are also used in making the liners. The membranes are covered with a tough, nonwoven, synthetic fabric (geotextiles) and then covered with a thick layer of fine gravel or sand to protect the liner from accidental punctures. A system of slotted pipes and pumps is installed to collect all the leachate from the bottom of the landfill (Figure 18.38, *left*). The collected leachate is then treated on or off the site. The principal soil-related concerns are the requirement for suitable sources of sand and gravel, of soil for daily cover, for clayey material to form the final cover, and for topsoil to support protective vegetation.

Environmental Impacts of Landfills

Modern regulations require that wastes be buried in carefully located and designed containment type sanitary landfills. As a result, the number of landfill sites has been reduced; in the

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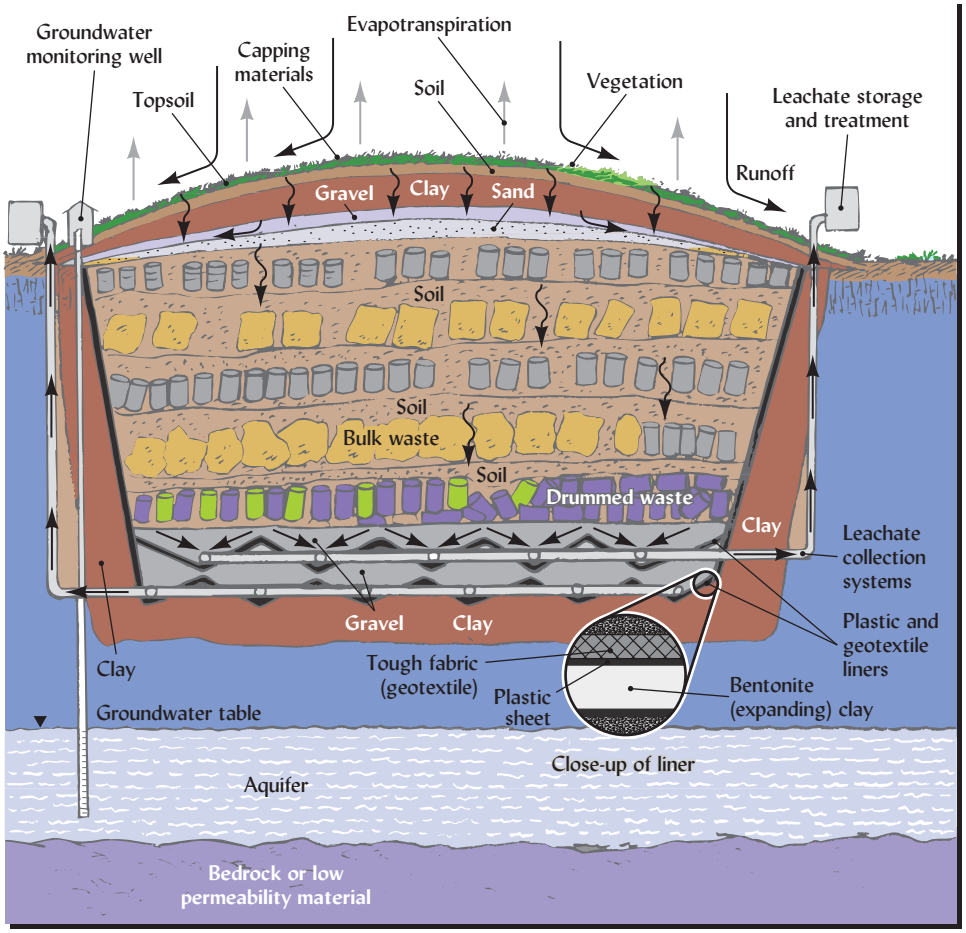

Figure 18.37 *A containment-type landfill is designed to collect all the leachate and pump it out for storage and treatment. The bottom of the landfill cell is sealed with a waterproof geomembrane which is protected by a covering of geotextile and gravel. Versions of this basic design are used for more hazardous wastes or when soil conditions on the site are unsuitable for a natural attenuation landfill design, illustrated in Figure 18.35.* (Diagram courtesy of Ray R. Weil)

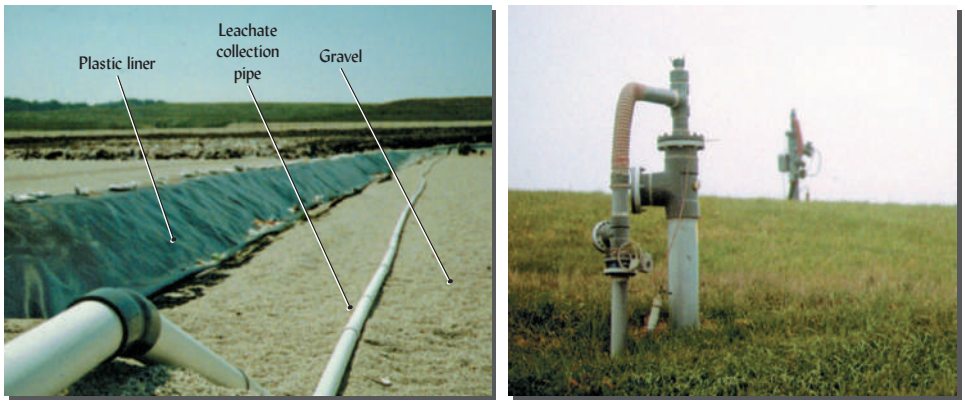

Figure 18.38 *Engineered systems for the collection of leachate and gas emissions in a containment landfill.* (Left) *A black geomembrane liner covered with white pea gravel and a leachate collection pipe in a new cell being prepared in a containment-type landfill. The pollutant-laden leachate will be piped to a treatment facility.* (Right) *Gas wells collecting landfill gas (a mixture of mainly methane and carbon dioxide) from anaerobic decomposition in a completed landfill cell. The methane is used to generate electric power.* (Photos courtesy of Ray R. Weil)

United States from about 16,000 in 1970 to fewer than 2000 in 2014. The remaining landfills are mostly very large, highly engineered containment-type systems. A major concern with regard to landfills is the potential water pollution from the rainwater that percolates through the wastes, dissolving and carrying away all manner of organic and inorganic contaminants (see Table 18.14). In addition to the general load of oxygen-demanding dissolved organic carbon compounds, many of the contaminants in landfill leachate are highly toxic and would create a serious pollution problem if they reached the groundwater under the landfill.

In addition to efficiency of resource use, avoidance of particular landfill management problems is another reason that the organic components of refuse (mainly paper, yard trimmings, and food waste) should be composted to produce a soil amendment rather than

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landfilled. First, as these materials decompose in a finished landfill, they lose volume and cause the landfill to settle and the landfill surface to subside. This physical instability severely limits the uses that can be made of the land once a landfill is completed.

Second, decomposition of the organic refuse produces undesirable liquid and gaseous products. Within a few weeks, decomposition uses up the oxygen in the landfill, and the processes of anaerobic metabolism take over, changing the cellulose in paper wastes into butyric, propionic, and other volatile organic acids, as well as hydrogen and carbon dioxide. After a month or so, methane-producing bacteria become dominant, and for several years (or even decades) a gaseous mixture of about one-third carbon dioxide and two-thirds methane (known as *landfill gas*) is generated in quantity. Anaerobic decomposition in landfills also emits other harmful gases, the effects of which are less well known.

The production of methane gas by the anaerobic decomposition of organic wastes in a landfill can present a very serious explosion hazard if this gas is not collected and used as fuel (Figure 18.38, *right*). Where the soil is rather permeable, the gas may diffuse into basements up to several hundred meters away from the landfill. A number of fatal explosions have occurred by this process. The methane also diffuses through the final cover to the atmosphere making landfills a significant source of greenhouse gas emissions, worldwide.

Land Use After Completion

A modern landfill may be designed to receive wastes for several decades, but eventually it will become filled to capacity and will have to be closed. The management and land use after completion and closure of a landfill is an important part of proper landfill design. This long-term management requires the application of soils' knowledge at all stages. The site will receive a final engineered soil cover and installation of landscaping vegetation, all of which will have to be maintained to prevent erosion, landslides, and exposure of wastes. Leachate treatment and monitoring of runoff and groundwater will have to continue, indefinitely. Gas collection and utilization will continue for decades.

Most modern landfills occupy large areas (commonly 100s of hectares) of highly valuable land located in or near major urban centers. As such, the closed landfill sites represent opportunities for beneficial land uses. However, there are limitations. The presence of leachate and landfill gases could present hazards for buildings. But the most common hazard is the land subsidence that occurs as the wastes inside the landfill settle and decay. The settling takes place in stages. Some settlement is almost immediate as the easily compressed waste are compacted under the weight of machines and final cover soil. Additional subsidence takes place during the next few months as wastes settle and creep downslope. The decay of organic waste components occurs more slowly and cause additional settling for a period of 25–30 years. In the end, the land surface typically settles by 25%–30% of the thickness of the layers of compacted waste inside the finished landfill.

While the hazards just mentioned prevent most building construction on these sites, many closed landfills have been developed into parks popular with urban dwellers and wildlife, alike. A number of golf courses and athletic fields have been constructed on closed landfills. Some cities have taken advantage of the artificial hills (mounds of wastes and soil layers) to provide such activities as skiing in snowy regions. Storm water retention ponds on landfill sites have been multipurposed to also serve as aesthetic landscape elements and sites for recreational fishing and boating. All these uses help pay for the cost of maintaining the landfill site, and all require the continuing application of soils knowledge in their management.

18.10 RADIONUCLIDES IN SOIL

Soils contain small quantities of ^{238}U, ^{40}K, ^{87}Rb, ^{14}C, and a number of other naturally occurring radioactive isotopes (radionuclides) that are characterized by long half-lives and give off minute amounts of radiation in the form of alpha particles (bundles of two neutrons and two protons) and beta particles (positive or negatively charged particles). As a radionuclide decays, its nucleus discharges these particles, transforming the atom into a different isotope or element with a lighter nucleus. The time it takes for one-half of the atoms of a particular

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radioactive isotope to undergo such decay is termed the *half-life* of the isotope. After ten half-lives, 99.1% of the original atoms will have decayed. The intensity of radioactivity present—or, more precisely, the rate of radioactive decay—is expressed using the SI unit *becquerel* (Bq), which represents one decay per second. An older metric unit, still in wide use, is the *curie* (Ci), which equals 3.7×10^{10} Bq.[8]

Radioactivity from Nuclear Fission

The process of nuclear fission, in connection with atomic weapons testing and nuclear power generation, has contaminated soils with a number of additional radionuclides. However, only two of these are sufficiently long-lived to be of significance in soils: strontium 90 (half-life = 28 years) and cesium 137 (half-life = 30 years). The average level of ^{90}Sr in soil in the United States is about 14.4 kilobecquerels per square meter (kBq/m^2) or 388 millicuries per square kilometer (mCi)/km^2. The average level for ^{137}Cs is about 22.9 kBq/m^2 (620 mCi/km^2). The levels of radioactivity caused by nuclear fallout are quite small compared to that for naturally occurring radionuclides. For example, for naturally occurring ^{40}K the average level is about 1900 kBq/m^2 (51,800 mCi/km^2).

Partly because of the cation-exchange properties of soils, the levels of these fission radionuclides found in most soils are not high enough to be hazardous. Most of the ^{90}Sr and ^{137}Cs reaching the soil is adsorbed by the soil colloids in exchange for other cations previously adsorbed, with the result that plants take up mainly the replaced cations rather than the added radionuclides (see Section 8.8). Even during the peak periods of weapons testing in the early 1960s, soils did not contribute significantly to the level of these nuclides in plants. Atmospheric fallout directly onto foliage was the primary source of radionuclides in the food chain. Consequently, only in the event of a catastrophic supply of fission products could toxic soil levels of ^{90}Sr and ^{137}Cs be expected.

Nuclear Accident at Chernobyl[9]

Such high levels of ^{90}Sr and ^{137}Cs, as well as ^{131}I, did contaminate soils in Ukraine, Scandinavia, and Eastern Europe in the wake of the 1986 reactor meltdown at Chernobyl in Ukraine (then part of the Soviet Union). While the accident deposited more than 200 kBq/m^2 of radioactivity on soils as far away as the United Kingdom, the dangerous high levels of contamination occurred closer to the reactor and resulted in the designation of a 2600 km^2 exclusion zone from which everyone was evacuated and to which no one has been allowed to return since. This Chernobyl exclusion zone is still one of the world's most toxic environments, with ^{137}Cs levels ranging from 30 kBq/m^2 to as high as 70,000 kBq/m^2. To put these levels in perspective, 30 kBq/m^2 is the soil contamination level usually considered unsafe for use in farming.[10]

The successional vegetation has helped maintain the contamination by protecting the soil surface from erosion that might have washed or blown away some of the contaminant, while cycling of Cs and Sr by deep rooted trees (in a manner analogous to that shown for Ca in Figure 2.27) has kept the radionuclides from leaching out of the soil profile. Scientists studying the ecosystems growing up on the abandoned farmland have found mutation-induced deformities in young trees and reduced fertility and life spans in birds. Although not officially sanctioned, some people residing nearby wander into the exclusion zone to graze cattle, although the milk from these cattle fails safety tests. Likewise, locals enter the zone to gather wild mushrooms, a local food delicacy, although those with deeper mycelia tend to be dangerously radioactive (Figure 18.39).

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[8]The curie was named after Marie and Pierre Curie, Polish scientists who discovered radium, an element that decays at the rate of 3.7×10^{10} Bq/g. The becquerel was named after Antoine Henry Becquerel, a French scientist who discovered radioactivity in uranium.

[9]For an update on the ecological consequence of the Chernobyl disaster see Little and Bird (2013).

[10]Depending on the depth of sampling (usually 5–10 cm) and the bulk density of the soil (usually 0.8–1.5 Mg/m^3) the 30 kBq/m^2 threshold on a mass rather than area basis would be approximately 0.5 kBq/kg soil. See footnote 11 in Chapter 4.

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Figure 18.39 *Women gather mushrooms near Visokoye, Belarus, under a sign that reads "Radiation danger! Cultivation and harvesting of agricultural crops, haymaking and cattle grazing are prohibited." The exclusion zone around Chernobyl, Ukraine, is still highly contaminated with radionuclides.* (Photo courtesy of Caroline Penn/Panos Pictures)

Nuclear Accident at Fukushima

Another nuclear catastrophe occurred in 2011 at the Fukushima Dai-ichi nuclear power plant. As a result of a large earthquake and associated tsunami that hit Japan on March 11, 2011, massive amounts of radionuclides were released into the water and air over a period of several weeks before the leakage was contained. As the reactor was on the coast, much of the radiative material fell in the ocean, but some 20% of the radioactive substances released were deposited on land. Of greatest concern was soil contamination with radioactive Cesium. Surface soil samples collected in Fukushima Prefecture some 30–40 km downwind from the stricken reactor were found to contain radiation from these two radionuclides at levels of up to 300–400 kBq/kg (equivalent to about 18,000–24,000 kBq/m^2), with many locations registering between 10 and 100 kBq/kg. The area normally produces almost half a million Mg of rice for human consumption. To avoid health risks to the rice-eating public, the government of Japan prohibited rice planting in fields with Cs levels in the soil exceeding 5.0 kBq/kg. However, even with this planting restriction in place, some rice harvested the following season from that area was soon found to contain in excess of the 0.5 kBq/kg safety limit set for rice under the Japanese Food Sanitation Law. The ensuing public panic about rice (and other produce) from Fukushima Prefecture effectively put thousands of farmers out of business and threatened to end the region's 2000 year old traditional lifestyle.

Fortunately, considerable research has been accomplished on the behavior of radionuclides in the soil–plant system.

Strontium 90. In the soil–plant–animal system, ^{90}Sr behaves very much like calcium, to which it is closely related chemically (see periodic table, Appendix B). It enters the soil from the atmosphere in soluble forms and is quickly adsorbed by the colloidal fraction, both organic and inorganic. It is taken up by plants and assimilated much like calcium. Contamination of forages and, ultimately, of milk by this radionuclide is of concern, as the ^{90}Sr could potentially be assimilated into the bones of the human body. Fortunately, when it exchanges with aluminum or hydrogen ions adsorbed on the colloids in an acid soil, it comprises such a minute fraction of the exchangeable cations that its availability is quite low. However, should these soils be limed, the large quantities of added calcium are likely to cause the desorption of the strontium from the exchange sites, making it more available for leaching and plant update. However, the preponderance of calcium in the limed soil solution would compete with strontium for uptake by plant roots, and so reduce the amount of strontium entering the food chain.

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Cesium 137. Cesium has a high level of biological availability as plants absorb it much as they do potassium. The radiation effects for cesium are quite long term as the radioactive half-lives for ^{134}Cs and ^{137}Cs are 2 and 30 years, meaning highly contaminated soils might remain radioactively hazardous for decades to centuries. Although chemically similar to potassium, in certain soils, cesium tends to be less readily available to plants. Apparently, ^{137}Cs is firmly fixed by vermiculite and related interstratified minerals. The fixed nuclide is nonexchangeable, much as is fixed potassium in some interlayers of clay (see Box 8.3 and Section 14.15). Plant uptake of ^{137}Cs from vermiculitic soils is very limited. Where vermiculite and related clays are absent, as in most highly weathered soils and volcanic soils, ^{137}Cs uptake is more rapid. In any case, the soil tends to dampen the movement of ^{137}Cs into the food chain of animals, including humans.

Iodine 131. When it partially melted down, the nuclear reactor at Chernobyl emitted significant quantities of ^{131}I, which accumulates in the human thyroid. People in the area around the reactor have since suffered an increased incidence of thyroid cancer. Because of its short half-life (8.1 days), reactions in the soil and movement through the soil–plant–animal food chain are less significant than contamination of drinking water, inhalation of contaminated dust particles, and contamination of edible plant foliage.

Research is underway to take advantage of plant uptake of radionuclides in phytoremediation exercises. Certain plants, such as sunflowers, are being used to remove ^{90}Sr and ^{137}Cs from ponds and soils near the site of the Chernobyl nuclear disaster. Indian mustard is also being used in nearby sites to remove such nuclide contaminants.

Radioactive Wastes[11]

In addition to radionuclides added to soils because of weapons testing and nuclear power plant accidents, soils may interact with radioactive waste materials that have leaked from their holding tanks or have been intentionally buried for disposal. Plutonium, uranium, americium, neptunium, curium, and cesium are among the elements whose nuclides occur in radioactive wastes. These wastes are generated by research and medical facilities (where the radionuclides are used in cancer therapy and the like), and at power plants and weapons manufacturing sites.

Because of the secrecy and lack of regulation associated with the latter, they constitute some of the most polluted locations on Earth. For example, the U.S. Defense Department's now-abandoned plutonium-production complex at Hanford, Idaho, represents one of the biggest environmental cleanup challenges in the world. Among the hazards plaguing that site are hundreds of huge, in many cases leaking, underground tanks, in which high-level radioactive wastes have been stored for decades. Billions of cubic meters of soil and water have been contaminated with radioactive wastes at U.S. weapons manufacturing sites and at similar, equally polluted sites in the former Soviet Union.

Plutonium Toxicity. Plutonium 239, a major pollutant at these sites, is dangerous both because of its intense radioactivity and because of its high level of toxicity to humans. The ^{239}Pu itself is quite immobile in soils, having a K_d estimated at about 1000. Nor is it taken up readily by plants, so it does not accumulate along terrestrial food chains. It does, however, accumulate in algae. Furthermore, oily liquid wastes carrying ^{239}Pu seep into the groundwater and nearby rivers, and contaminated surface soil blows in the desert wind, spreading the radionuclides for many kilometers. Cleanup may be impossible at some of these former weapons sites; the agencies responsible are struggling merely to stabilize and contain the contamination. With a half-life of 24,400 years, ^{239}Pu contamination is a problem that will not go away.

Low-Level Wastes. Low-level radioactive wastes also present some environmental challenges. Even though the waste materials may be solidified before being placed in shallow land burial pits, some dissolution and subsequent movement in the soil are possible. Nuclides in wastes vary greatly in water solubility, uranium compounds being quite soluble, compounds

[11]For a description of the environmental challenges at the Hanford site, see Zorpette (1996).

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Table 18.15
CONCENTRATIONS OF SEVERAL BREAKDOWN PRODUCTS OF URANIUM 238 AND THORIUM 232 (NUCLEOTIDES) IN SIX DIFFERENT SOIL SUBORDERS IN LOUISIANA, USA
Note marked differences among levels in the different soils.

Soil suborder	No. of samples	^{238}U breakdown products, Bq/kg			^{232}Th breakdown products, Bq/kg		
		^{226}Ra	^{214}Pb	^{214}Bi	^{212}Pb	^{137}Cs	^{40}K
Udults	22	37.3	27.7	28.9	27.4	16.7	136
Aquults	24	30.4	36.7	38.1	50.0	10.9	100
Aqualfs	37	51.1	38.3	36.6	59.7	13.5	263
Aquepts	93	92.2	47.6	45.2	63.8	16.1	636
Aquolls	57	90.4	45.8	44.7	59.5	8.7	608
Hemists	18	136.3	49.4	49.0	74.9	19.4	783

From Meriwether et al. (1988).

of plutonium and americium being relatively insoluble, and cesium compounds being intermediate in solubility. Cesium, a positively charged ion, is adsorbed by soil colloids. Uranium is thought to occur as a UO_2^{2+} ion that is also adsorbed by soil. The charge on plutonium and americium appears to vary, depending on the nature of the complexes these elements form in the soil.

There is considerable variability in the actual uptake by plants of these nuclides from soils, depending on such properties as pH and organic matter content. The uptake from soils by plants is generally lowest for plutonium, highest for neptunium, and intermediate for americium and curium. Fruits and seeds are generally much lower in these nuclides than are leaves, suggesting that grains may be less contaminated by nuclides than forage crops and leafy vegetables.

Since soils are being used as burial sites for low-level radioactive wastes, care should be taken that soils are chosen whose properties discourage leaching or significant plant uptake of the chemicals. Data in Table 18.15 illustrate differences in the ability of different soils to hold breakdown products of two radionuclides. It is evident that monitoring of nuclear waste sites will likely be needed to assure minimum transfer of the nuclides to other parts of the environment.

18.11 RADON GAS FROM SOILS[12]

The Health Hazard

The soil is the primary source of the colorless, odorless, tasteless radioactive gas ***radon***, which has been shown to cause lung cancer. Although landfills containing radioactive wastes have been known to emit radon gas at elevated concentrations, most concern regarding this potential toxin is directed toward radon that occurs naturally in soils. Therefore, radon is not usually considered a soil pollutant because it has not been introduced into the soil by human activity. Nonetheless, radon gas is thought to be a serious environmental health hazard when it moves from the soils and accumulates inside buildings. Deaths from breathing in radon are estimated at about 20,000 per year in the United States, some 10–50 times more numerous than deaths caused by contaminants in drinking water. The gas may be a causal factor in about 10% of lung cancer cases.

[12]For a straightforward discussion of the hazards of indoor radon and what you can do to protect yourself, see U.S. EPA (2012). For a review of the radon in soils and geologic material with a focus on mapping radon hazard areas, see Appleton (2007).

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The health hazard from this gas stems from its transformation to radioactive polonium isotopes, which are solids that tend to attach to dust particles. The polonium-contaminated dust particles may lodge in the lungs, where alpha-particle radiation emitted by the polonium can penetrate the lung tissue and cause cancer. The principal concern is with radon accumulation in homes, offices, and schools where people breathe the air in basement or ground-level rooms for extended periods.

How Radon Accumulates in Buildings

Geologic Factors. Radon originates from uranium (^{238}U) found in minerals, sorbed on soil colloids, or dissolved in groundwater. Over billions of years, the uranium undergoes radioactive decay forming radium, which in turn gives off radiation over thousands of years and transforms into radon (Figure 18.40). Both uranium and radium are solids; however, radon is a gas that can diffuse through pores and cracks and emerge into the atmosphere. Soils and rocks that contain high concentrations of uranium will likely produce large amounts of radon gas. Soils formed from certain highly deformed metamorphic rocks and from marine sediments, limestones, and coal or oil-bearing shales tend to have the highest potential levels for radon production. However, nearby houses built on soils formed from the same parent material may differ widely in their indoor radon concentrations (Figure 18.41, *right*), the difference being due to variations in soil properties and/or house construction.

Soil Properties. To become a hazard, radon must travel from its source in the underlying rock or soil, up through overlying soil layers, and finally into an enclosed building where it might accumulate to unhealthful concentrations. It must also make this trip quite rapidly, because the half-life of radon is only 3.8 days. Within several weeks, radon completely decays to polonium, lead, and bismuth, radioactive solids that last for only minutes. Whether significant quantities of radon reach a building foundation depends mainly on two factors: (1) the distance that the radon must travel from its source and (2) the permeability of the soil through which it travels. Since radon is an inert gas, the soil does not react with it, but merely serves as a channel through which the gas moves.

As explained in Sections 7.1 and 7.2, gases move through soil both by diffusion and by mass flow (convection). The rate of radon diffusion through a soil depends on the total soil porosity (more so than on pore size) and the degree to which the pores are filled with water. Radon diffuses through air-filled pores about 10,000 times faster than through water-filled pores. Movement is most rapid through sandy or gravelly soil layers that tend to hold little water. Therefore, some of the highest indoor radon concentrations have been found in houses where only a thin, well-drained, gravelly soil separates the house foundation from uranium-rich rock. At the other extreme, a thick, wet clay layer would provide an excellent barrier

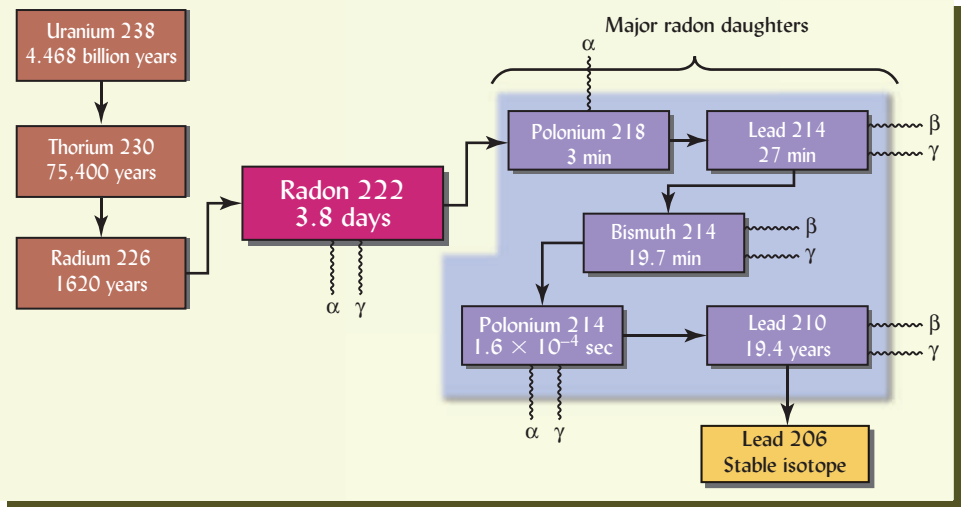

Figure 18.40 *Radon decay chain showing the element name, atomic weight and half-life for each isotope. Radioactive decay of uranium 238 in soils that results in the formation of inert but radioactive radon. This gas emits alpha (α) particles and gamma (γ) rays and forms radon daughters that are capable of emitting alpha (α) and beta (β) particles and gamma (γ) rays. The alpha particles damage lung tissue and cause cancer. Radon gas may account for about 20,000 deaths annually in the United States.* (Diagram courtesy of Ray R. Weil)

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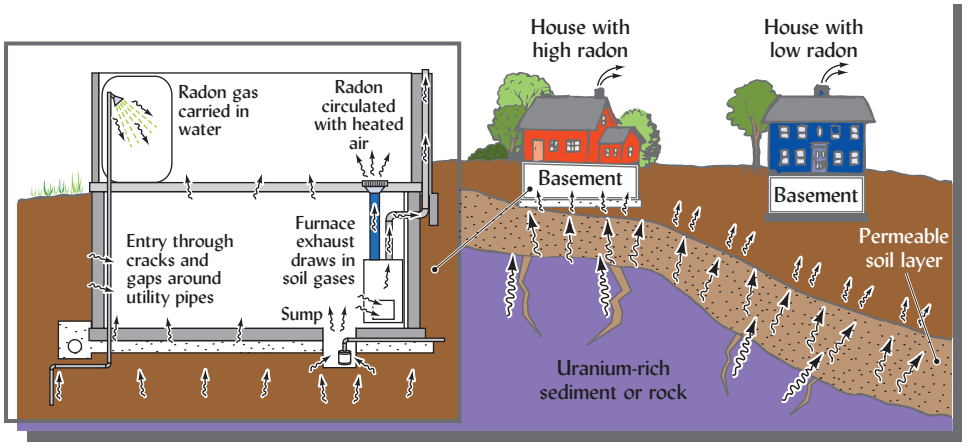

Figure 18.41 *The foundation of a house, as well as the nature of the soil and rocks in the vicinity, helps determine whether dangerous levels of radioactive radon gas are likely to accumulate inside.* (Right) *Levels of indoor radon can vary greatly from one house to another. On a regional basis, radon is likely to be highest where the soils are formed from uranium-bearing parent materials. The soil that underlies a house plays a role in the movement of radon gas from its source in rock and soil minerals to the air inside the house. Dry, coarse-textured permeable soil layers allow much faster diffusion of radon gas than does a wet or fine-textured soil. If soils underlying a house are relatively impermeable, radon movement will be so slow that nearly all of the radon emitted will have decayed before it can reach the house foundation.* (Left) *Once it arrives at a house foundation, radon may enter through a variety of openings, such as cracks in the foundation blocks, joints between the walls and concrete floor, and gaps where utility pipes enter the house. Radon risks are greatest during cold weather. Heated air escapes up the furnace chimney but windows are sealed, creating negative air pressure inside the house, which, in turn, draws in air from the soil.*
(Diagrams courtesy of Ray R. Weil)

against radon diffusion. Convective airflow, which is mainly stimulated by rainwater entering the soil and by changes in atmospheric pressure, may play a significant role in radon movement during stormy weather.

Building Factors. Because concrete is an effective barrier against diffusion, radon enters the building primarily by convective flow, which is driven by the difference between the air pressure inside the building and in the soil air around the foundation. Open upper-story windows, exhaust pipes, and chimneys tend to exhaust air from a building, lowering the internal air pressure and drawing in air from outside (Figure 18.41, *left*). If the basement has no open windows, air will be drawn into the building through cracks in the basement walls and floors, and around openings where utility pipes enter the basement. Since modern airtight buildings permit little exchange of air with the outside, radon can accumulate to harmful levels. A building with a crawl space between the first floor and the soil surface will draw in fresh outside air from the atmosphere, but one with a basement or a slab foundation directly on the soil will draw in soil air that may be enriched in radon.

Radon Testing and Remediation

Testing. Since the occurrence of high radon levels cannot be accurately predicted, the only sure way to determine the risk of radon is to test for its presence. Testing is usually carried out in two stages. The first uses an inexpensive (about $15) charcoal canister, which is placed in the test area, unsealed, and left to absorb radon for the specified period (usually three days). The canister should be placed in the most high-risk location in the building—for example, in a basement bedroom without cross ventilation—during a time when the building is heated. After the test period, the canister is resealed and sent to a lab where the amount of radon absorbed can be measured and related to the radon concentration that was in the air. If the results suggest a radon level above 4 piCi/L (148 Bq/m^3), the U.S. EPA advises that a long-term test be conducted using a somewhat more expensive alpha-track detector for a period of 3–12 months. If the long-term test also suggests levels above 4 piCi/L, modifications should be made to the building to reduce the accumulation of radon inside.

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Remediation. Depending on the levels of radon and the condition of the building, the modification may be as simple as caulking cracks in the floor and walls and filling gaps around utility-pipe entrances. Remediation of higher radon levels may require alterations that are more extensive. Ventilation of the room with outside air can prevent unhealthful radon buildup, but a more energy-efficient solution is a subslab ventilation system. For the latter, perforated pipes are installed in a layer of gravel under the foundation slab, and the air pressure there is lowered either by a mechanical fan or by convective draw from a special chimney. In this way, gas coming from the soil is intercepted and redirected to the atmosphere before it can enter the building. Installation of a subslab ventilation system is much less expensive during new construction than as a retrofit, and is now standard practice in many areas with high-uranium soils.

18.12 CONCLUSION

Three major conclusions may be drawn about soils in relation to environmental quality. First, since soils are valuable resources, they should be protected from environmental contamination, especially that which does permanent damage. Second, because of their vastness and remarkable capacities to absorb, bind, and break down added materials, soils offer promising mechanisms for the disposal and utilization of many wastes that otherwise may contaminate the environment. Third, soil contaminants and the products of their breakdown in soil reactions can be toxic to humans and other animals if the soil is ingested or the contaminants move from the soil into plants, soil fauna, the air, and—particularly—into water supplies.

To gain a better understanding of how soils might be used and yet protected in waste-management efforts, soil scientists devote a considerable share of their research efforts to environmental-quality problems. Furthermore, soil scientists have much to contribute to the research teams that search for better ways to clean up environmental contamination. Some of the most promising technological advances have been in the field of bioremediation, in which the biological processes of the soil are harnessed to effect soil cleanup. Finding appropriate sites where soils can be safely used to clean up or store hazardous wastes involves geographic information about soils, the topic of the next chapter.

STUDY QUESTIONS

1. What agricultural practices contribute to soil and water pollution, and what steps must be taken to reduce or eliminate such pollution?
2. Discuss the types of reactions pesticides undergo in soils, and indicate what we can do to encourage or prevent such reactions.
3. Discuss the environmental problems associated with the disposal of large quantities of sewage sludge on agricultural lands, and indicate how the problems could be alleviated.
4. What is *bioremediation*, and what are its advantages and disadvantages compared with physical and chemical methods of handling organic wastes?
5. Even though large quantities of the so-called heavy metals are applied to soils each year, relatively small quantities find their way into human food. Why?
6. Compare the design, operation, and management of today's containment landfills with the natural attenuation type most common 30 years ago, and indicate how the changes affect soil and water pollution.
7. What are *organoclays*, and how can they be used to help remediate soils polluted with nonpolar organic compounds?
8. Soil organic matter and some silicate clays chemically sorb some organic pollutants and protect them from microbial attack and leaching from the soil. What are the implications (positive and negative) of such protection for efforts to reduce soil and water pollution?
9. What radionuclides are of greatest concern in soil and water pollution, and why are they not more readily taken up by plants?
10. What are the comparative advantages and disadvantages of in situ and ex situ means of remediating soils polluted with organic compounds?
11. What are two approaches to *phytoremediation*, and for what kinds of pollutants are they useful? Explain.
12. Suppose a nickel-contaminated soil 15 cm deep contained 800 mg/kg Ni. Vegetation was planted to remove the nickel by phytoremediation. The aboveground plant parts average 1% Ni on a dry-weight basis and produce 4000 kg/ha of harvestable dry matter. If two harvests are possible per year, how many years will it take to reduce the Ni level in the soil to a target of 80 mg/kg?

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REFERENCES

Adriano, D. C. 2001. *Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability, and Risks of Metals*. Springer, New York, p. 880.

Alexander, M. 2000. "Aging, bioavailability, and overestimation of risk from environmental pollutants." *Environmental Science & Technology* **34**:4259–4265.

Altieri, M. A. 1995. *Agroecology: The Science of Sustainable Agriculture*. 2nd ed. Westview Press, Boulder, CO, p. 448.

Appleton, J. D. 2007. "Radon: Sources, health risks, and hazard mapping." *AMBIO: A Journal of the Human Environment* **36**:85–89.

Barth, J. A. C., P. Grathwohl, H. J. Fowler, A. Bellin, M. H. Gerzabek, et al. 2009. "Mobility, turnover and storage of pollutants in soils, sediments and waters: Achievements and results of the EU project AquaTerra. A review." *Agronomy for Sustainable Development* **29**:161–173.

Berti, W. R., and L. W. Jacobs. 1996. "Chemistry and phytotoxicity of soil trace elements from repeated sewage sludge applications." *Journal of Environmental Quality* **25**:1025–1032.

Beyer, W. N., R. L. Chaney, and B. M. Mulhern. 1982. "Heavy metal concentration in earthworms from soil amended with sewage sludge." *Journal of Environmental Quality* **11**:381–385.

Bøhn, T., M. Cuhra, T. Traavik, M. Sanden, J. Fagan, and R. Primicerio. 2014. "Compositional differences in soybeans on the market: Glyphosate accumulates in roundup ready GM soybeans." *Food Chemistry* 153:207–215.

Boyle, M. 1988. "Radon testing of soils." *Environmental Science & Technology* **22**:1397–1399.

Bragg, J. R., R. C. Prince, E. J. Harner, and R. M. Atlas. 1994. "Effectiveness of bioremediation for the *Exxon Valdez* oil spill." *Nature* **368**:413–418.

Cao, X., and L. Q. Ma. 2004. "Effects of compost and phosphate on plant arsenic accumulation from soils near pressure-treated wood." *Environmental Pollution* **132**:435–442.

Capowiez, Y., F. Bastardie, and G. Costagliola. 2006. "Sublethal effects of imidacloprid on the burrowing behaviour of two earthworm species: Modifications of the 3D burrow systems in artificial cores and consequences on gas diffusion in soil." *Soil Biology and Biochemistry* **38**:285–293.

Carson, R. 1962. *Silent Spring*. Houghton Mifflin, Cambridge, MA, p. 378.

Chaney, R. L. 1990. "Public health and sludge utilization, Part II." *Biocycle* **31**(10):68–73.

Cuhra, M., T. Traavik, M. Dando, R. Primicerio, D. F. Holderbaum, and T. Bøhn. 2015. "Glyphosate-residues in roundup-ready soybean impair *Daphnia magna* lifecycle." *Journal of Agricultural Chemistry and Environment* 4:24.

Defoe, P. P., G. M. Hettiarachchi, C. Benedict, and S. Martin. 2014. "Safety of gardening on lead- and arsenic-contaminated urban brownfields." *Journal of Environmental Quality* **43**:2064–2078.

Dowdy, R. H., C. E. Clapp, D. R. Linden, W. E. Larson, T. R. Halbach, and R. C. Polta. 1994. "Twenty years of trace metal partitioning on the Rosemount sewage sludge watershed." In C. E. Clapp, W. E. Larson, and R. H. Dowdy (eds.). *Sewage Sludge: Land Utilization and the Environment*. Soil Science Society of America, Madison, WI, pp. 149–155.

Eccles, H. 2007. *Bioremediation*. Taylor & Francis, New York, p. 372.

Edwards, C. A. 1978. "Pesticides and the micro-fauna of soil and water." In I. R. Hill and S. J. Wright (eds.). *Pesticide Microbiology*. Academic Press, London, pp. 603–622.

El-Naggar, J. B., and N. E.-H. A. Zidan. 2013. "Field evaluation of imidacloprid and thiamethoxam against sucking insects and their side effects on soil fauna." *Journal of Plant Protection Research* **53**:375–387.

Fernandez-Cornejo, J., R. Nehring, C. Osteen, S. Wechsler, A. Martin, and A. Vialou. 2014. "Pesticide use in U.S. Agriculture: 21 selected crops, 1960-2008." Economic Information Bulletin 124. U.S. Department of Agriculture, Economic Research Service. www.ers.usda.gov/publications/eib-economic-information-bulletin/eib124.aspx.

Furr, A. K., A. W. Lawerence, S. S. C. Tong, M. C. Grandolfo, R. A. Hofstader, C. A. Bache, W. H. Gutemann, and D. J. Lisk. 1976. "Multielement and chlorinated hydrocarbon analysis of municipal sewage sludges of American cities." *Environmental Science & Technology* **10**:683–687.

Gaynor, J. D., D. C. MacTavish, and W. I. Findlay. 1995. "Atrazine and metolachlor loss in surface and subsurface runoff from three tillage treatments in corn." *Journal of Environmental Quality* **24**:246–256.

Gilliom, R. J., J. E. Barbash, C. G. Crawford, P. A. Hamilton, J. D. Martin, N. Nakagaki, L. H. Nowell, J. C. Scott, P. E. Stackelberg, G. P. Thelin, and D. M. Wolock. 2006. "The quality of our nation's waters: Pesticides in the nation's streams and ground water, 1992–2001," USGS Circular 1291. U.S. Geological Survey, Reston, VA, p. 172. http://pubs.usgs.gov/circ/2005/1291/.

Hazen, T. C. 1995. "Savannah river site—a test bed for cleanup technologies." *Environmental Protection* (April):10–16.

Hazen, T. 2008. "Bioremediation: Hope/hype for environmental cleanup." Video lecture 57 min. https://www.youtube.com/watch?v=MT0qY3_n1kI

Hladik, M. L., D. W. Kolpin, and K. M. Kuivila. 2014. "Widespread occurrence of neonicotinoid insecticides in streams in a high corn and soybean producing region, USA." *Environmental Pollution* **193**:189–196.

FOR REFERENCE PURPOSES ONLY

Holmgren, G. G. S., M. W. Meyer, R. L. Chaney, and R. B. Daniels. 1993. "Cadmium, lead, zinc, copper, and nickel in agricultural soils of the United States of America." *Journal of Environmental Quality* **22**:335–348.

Jaynes, W. F., and S. A. Boyd. 1991. "Clay mineral type and organic compound sorption by hexadecyltrimethylammonium-exchanged clays." *Soil Science Society of America Journal* **55**:43–48.

Kjeldsen, P., M. Barlaz, A. Rooker, A. Baun, A. Ledin, and T. Christensen. 2002. "Present and long-term composition of MSW landfill leachate: A review." *Critical Reviews in Environmental Science and Technology* **32**:297–336.

Kreuger, R. F., and J. N. Seiber (eds.). 1984. *Treatment and Disposal of Pesticide Wastes*. American Chemical Society, Washington, D.C.

Little, J. B., and W. A. Bird. 2013. "A tale of two forests: Addressing postnuclear radiation at Chernobyl and Fukushima." *Environmental Health Perspectives*. http://ehp.niehs.nih.gov/121-a78/

McBride, M. B., B. K. Richards, T. Steenhuis, and G. Spiers. 1999. "Long-term leaching of trace elements in a heavily sludge-amended silty clay loam soil." *Soil Science* **164**:613–623.

McConnell, J. S., and L. R. Hossner. 1985. "pH-dependent adsorption isotherm of glyphosate." *Journal of Agricultural and Food Chemistry* **33**:1075–1078.

Meriwether, J. R., J. N. Beck, D. F. Keeley, M. P. Langley, R. N. Thompson, and J. C. Young. 1988. "Radionuclides in Louisiana soils." *Journal of Environmental Quality* **17**:562–568.

Meuser, H. 2010. *Contaminated Urban Soils*. Springer, New York, p. 340.

Pierzynski, G. M., J. T. Sims, and G. F. Vance. 2004. *Soils and Environmental Quality*, 3rd ed. CRC Press/Lewis Publishers, Boca Raton, FL.

Pimentel, D., and M. Burgess. 2014. "Environmental and economic costs of the application of pesticides primarily in the United States." In D. Pimentel and R. Peshin (eds.). *Integrated Pest Management*. Springer, Dordrecht, pp. 47–64.

Pritchard, P. H., J. G. Mueller, J. C. Rogers, F. V. Kremer, and J. A. Glaser. 1992. "Oil spill bioremediation: Experiences, lessons and results from the *Exxon Valdez* oil spill in Alaska." *Biodegradation* **3**:315–335.

Qian, X., R. M. Koerner, and D. H. Gray. 2002. *Geotechnical Aspects of Landfill Design and Construction*. Prentice Hall, Upper Saddle River, NJ, p. 716.

Reynolds, C. M., D. C. Wolf, T. J. Gentry, L. B. Perry, C. S. Pidgeon, B. A. Koenen, H. B. Rogers, and C. A. Beyrouty. 1999. "Plant enhancement of indigenous soil microorganisms: A low cost treatment of contaminated soils." *Polar Record* **35**(192):33–40.

Rose, M.T., T.R. Cavagnaro, C.A. Scanlan, T.J. Rose, T. Vancov, S. Kimber, I.R. Kennedy, R.S. Kookana, and L. Van Zwieten. 2016. "Impact of herbicides on soil biology and function", pp. 136–220 in *Advances in agronomy*, Vol. 136. Academic Press.

Ryan, J. A., K. G. Scheckel, W. R. Berti, S. L. Brown, S. W. Casteel, R. L. Chaney, J. Hallfrisch, M. Doolan, P. Grevatt, M. Maddaloni, and D. Mosby. 2004. "Reducing children's risk from lead in soil." *Environmental Science & Technology* **38**:18A–24A.

Simmons, R. W., R. L. Chaney, J. S. Angle, M. Kruatrachue, S. Klinphoklap, R. D. Reeves, and P. Bellamy. 2014. "Towards practical cadmium phytoextraction with noccaea caerulescens." *International Journal of Phytoremediation* **17**:191–199.

Sizmur, T., E. L. Tilston, J. Charnock, B. Palumbo-Roe, M. J. Watts, and M. E. Hodson. 2011. "Impacts of epigeic, anecic and endogeic earthworms on metal and metalloid mobility and availability." *Journal of Environmental Monitoring* **13**:266–273.

Sommers, L. E. 1977. "Chemical composition of sewage sludges and analysis of their potential use as fertilizer." *Journal of Environmental Quality* **6**:225–232.

Stokes, J. D., G. I. Paton, and K. T. Semple. 2005. "Behaviour and assessment of bioavailability of organic contaminants in soil: Relevance for risk assessment and remediation." *Soil Use and Management* **21**:475–486.

Stone, W. W., R. J. Gilliom, and J. D. Martin. 2014. "An overview comparing results from two decades of monitoring for pesticides in the nation's streams and rivers, 1992–2001 and 2002–2011."Scientific Investigations" Report 2014-5154. U.S. Geological Survey.

Strek, H. J., and J. B. Weber. 1982. "Adsorption and reduction in bioactivity of polychlorinated biphenyl (Aroclor 1254) to redroot pigweed by soil organic matter and montmorillonite clay." *Soil Science Society of America Journal* **46**:318–322.

Su, C., L. Jiang, and W. Zhang. 2014. "A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques." *Environmental Skeptics and Critics* **3**:24–38.

U.S. EPA. 1993. *Clean Water Act*, Sec. 503, Vol. 58, No. 32. U.S. Environmental Protection Agency, Washington, D.C.

USEPA. 2012. "A citizen's guide to radon: The guide to protecting yourself and your family from radon." U.S. EPA 402/K-12/002. U.S. Environmental Protection Agency, Indoor Environments Division, Washington, DC. http://www.epa.gov/radon/pdfs/citizensguide.pdf

U.S. EPA. 2014. "Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2012," EPA-530-F-14-001. U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/osw/nonhaz/municipal/pubs/2012_msw_fs.pdf.

van der Ent, A., A. M. Baker, R. Reeves, A. J. Pollard, and H. Schat. 2013. "Hyperaccumulators of metal and metalloid trace elements: Facts and fiction." *Plant and Soil* **362**:319–334.

FOR REFERENCE PURPOSES ONLY

Vijver, M. G., and P. J. van den Brink. 2014. "Macroinvertebrate decline in surface water polluted with imidacloprid: A rebuttal and some new analyses." *PLoS One* 9:e89837.

Weber, J. B., and C. T. Miller. 1989. "Organic chemical movement over and through soil." In B. L. Sawhney and K. Prown (eds.). *Reactions and Movement of Organic Chemicals in Soils*. SSSA Special Publication No. 22. Soil Science Society of America, Madison, WI.

Wise, D. L., D. J. Trantolo, E. J. Cichon, H. I. Inyang, and U. Stottmeister (eds.). 2000. *Bioremediation of Contaminated Soils*. Marcel Dekker, New York, p. 920.

Wiszniewska, A., E. Hanus-Fajerska, E. MuszyŃSka, and K. Ciarkowska. 2016. "Natural organic amendments for improved phytoremediation of polluted soils: A review of recent progress." *Pedosphere* 26:1-12.

Wong, C. T., M. K. Leung, M. K. Wong, and W. C. Tang. 2013. "Afteruse development of former landfill sites in Hong Kong." *Journal of Rock Mechanics and Geotechnical Engineering* 5:443–451.

Wu, G., H. Kang, X. Zhang, H. Shao, L. Chu, and C. Ruan. 2010. "A critical review on the bio-removal of hazardous heavy metals from contaminated soils: Issues, progress, eco-environmental concerns and opportunities." *Journal of Hazardous Materials* 174:1–8.

Xu, S., G. Sheng, and S. A. Boyd. 1997. "Use of organoclays in pollution abatement." *Advances in Agronomy* 59:25–62.

Zhang, X., T. Zhong, L. Liu, and X. Ouyang. 2015. "Impact of soil heavy metal pollution on food safety in China." *PLoS ONE* 10:e0135182.

Zorpette, G. 1996. "Hanford's nuclear wasteland." *Scientific American* (May):88–97. Comprehensive information on cleaning contaminated soils at abandoned industrial sites: http://www.epa.gov/brownfields/

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19 Geographic Soils Information

The soil/landscape portrait thus evolved is an artwork of the soil scientist . . .
—L. P. Wilding
We need . . . (soil) data that is geographically continuous, scalable and which includes uncertainty . . .
— Jon Hempel

Different soils underlie landscapes and land uses. (Ray R. Weil)

In order to make practical use of soil science principles, land managers, ecologists, and global modelers must all know not only the "what" and "why" of soils, but must also know the "where." If engineers planning an airport runway are to avoid the hazards of swelling clay soils, they must know *where* these troublesome soils are located. Irrigation experts may know what soil properties will be necessary for cost-efficient irrigation, but for their projects to succeed, they must also know *where* soils with these properties can be found. Almost any land-based project, from remediating an industrial brownfield to fertilizing a productive farm field, can benefit from geographic information about soils and soil properties. This chapter provides an introduction to some of the tools that tell us *what* is *where*.

In most cases, assembling, communicating, and using geographic information about soils involves various kinds of soil maps. Therefore, much of this chapter will explore the art and science of soil mapping at different scales and intensities. In so doing, we will introduce the use of tools as simple as a shovel and as sophisticated as space satellite-borne sensors and complex statistical models. Soil maps and the data that underpin them have become critical tools for scientists and policy makers attempting to understand and manage local, regional, and global environmental problems, resources, responses to climate change, and other interactions between humans and their home planet.

19.1 SOIL SPATIAL VARIABILITY IN THE FIELD

A quick review of Figure 7.10 (changing dissolved oxygen from the surface of a soil granule to its center) and Figure 12.24 (global distribution of organic carbon in the upper 1 m of the Earth's soils) reminds us that soil properties are variable at all scales. In this chapter we will consider soil variations occurring across distances having geographic meaning for land management—from a few meters to many kilometers.

When attempting to understand geographic variation of soils and how best to use each part of the land, it is often useful to analyze each site in terms of the five state factors that influence soil formation: *climate, parent material, organisms (including humans), topography*, and *time* (see Sections 2.2–2.7).

Climate usually influences soil variability at very large scales (regional differences), but where the landscape includes large water bodies or significant hills and mountains, rainfall and temperature may differ greatly over distances of 1 km or less. For example, the microclimate on north-facing slopes may differ in many ways from that on south-facing

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Figure 19.1 *Examples of small-scale soil variability. Along with the visible differences in soil color and stoniness, variations also existed in soil chemical, physical, and biological properties.* (Left) *Soil from four auger holes made about 50 m apart in an area underlain by sandy coastal plain parent material. The meter stick is labeled every 10 cm.* (Right) *Soil cores (3 cm diameter × 120 cm long; surface horizons to the left) obtained by hydraulic probe. The three cores in the foreground were taken 50 cm apart in an area underlain by clayey coastal plain parent material.* (Photos courtesy of Ray R. Weil)

slopes. Likewise, parent materials often vary in large-scale regional patterns (e.g., loess plateaus versus residual rock), but very small-scale differences may also occur (Figure 19.1). A soil scientist should always be alert for the possible presence of such localized parent materials as colluvial deposits at the foot of a slope or alluvium along stream courses. A field soil scientist also needs some training in botany so as to be able to recognize changes in plant community composition that might result from localized variations in soil properties such as in seasonally saturated depressions or calcareous outcroppings. As these latter examples suggest, most small-scale soil variations involve changes in topography, so an awareness of even subtle changes in relief is critical to understanding how soils change across a landscape.

Small-Scale Soil Variability

Soil properties are likely to change markedly across small distances: within a farm field, within a suburban house lot, and even within a single soil individual (as defined in Section 3.1). At this scale, variations most often relate to small changes in topography and thickness of parent material layers or to the effects of organisms (e.g., the effects of individual trees or past human management). Exposure of a calcareous horizon on the tops of hillocks because of wind and tillage erosion can result in dramatic small-scale variability in both surface soil color and plant vigor (see Figures 17.50 and 10.10). In some cases, the height or vigor of vegetation reflects the subsurface variability. In other cases, the changes in soil properties are detected by analyzing soil samples taken from many borings made throughout the plot of land in question. This and other techniques will be discussed in Section 19.2 with regard to the practical use of such observations in making soil maps.

Small-scale variability may be difficult to measure and not readily apparent to the casual observer. Variability in soil fertility often reflects past soil-management practices, as well as differences in soil profile characteristics. Analysis of small-scale variability may have practical uses in managing soil fertility for a given field or nursery (see Section 19.9).

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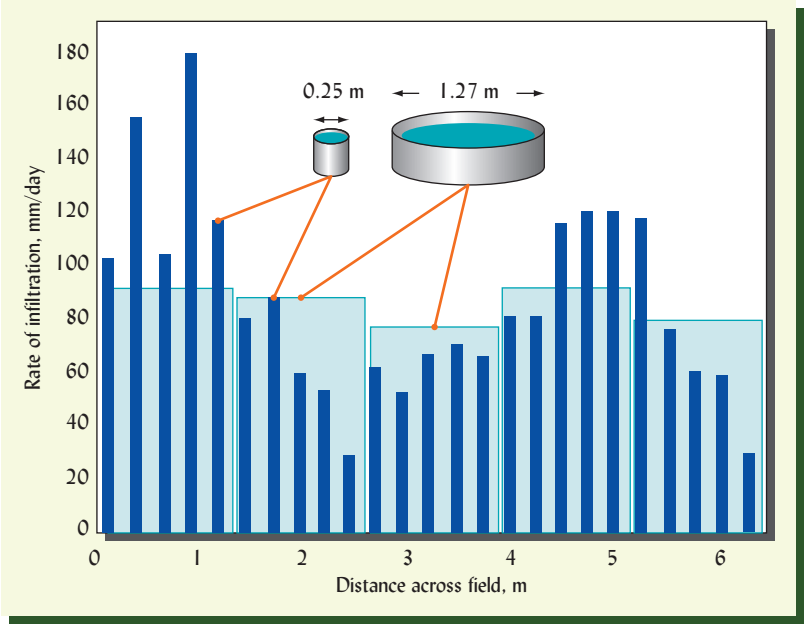

Figure 19.2 *The variability of soil properties is often inversely related to the scale of measurement. Here, infiltration rates were measured along a 6 m long transect using either many small diameter single ring infiltrometers (data shown by dark blue bars) or just a few large diameter infiltrometers (data shown by wide light blue bars). Some of the small ring measurements probably included a worm hole or crack while others did not. In contrast, all of the larger ring measurements included a few of these macropores. See also Figure 5.25.* [Diagram courtesy of Ray R. Weil, based on data cited in Baveye and Laba (2015)]

Chemical properties such as plant available phosphorus may be dramatically variable because of previous application of fertilizer in narrow bands or small spots. Biological soil properties such as microbial respiration or bacterial diversity are very sensitive to the presence of "hotspots" such as actively growing plant roots or lumps of animal waste. Physical soil properties such as water infiltration capacity can be especially variable due to such influences as earthworm burrows or cracks caused by clay shrinkage. Commonly, the variability measured is much reduced if the size of the sample is increased so that each sample analyzed includes a larger range of soil conditions (Figure 19.2). Another approach to reducing the variability among measurements is **composite sampling**, traditionally used for performing a soil test for fertility management (Section 16.11). A composite sample consists of a mixture of small cores from (usually 15–20) randomly scattered spots that collectively represent the entire area sampled, be that a 10 ha field or a 0.1 ha garden plot. The disadvantage of such sampling strategies is that the small-scale variability hidden by these approaches may be important to know about.

Medium-Scale Soil Variability

For many soil properties, variability across a landscape is related primarily to differences in a particular soil-forming factor, such as soil topography or parent material (Figure 19.3).

Landscape Models. An understanding of how the soil-forming factors influence soil properties in a landscape can provide a mental model that predicts what kinds of soils are likely to occur in different parts of a landscape. It is often possible to define sets of individual soils that tend to occur together in sequence across the land. Identifying one member of the set often makes it possible to predict soil properties in the landscape positions occupied by other members of the set. Such sets of soils include ***lithosequences*** (occurring across a sequence of parent materials), ***chronosequences*** (occurring across similar parent materials of varying age), and ***toposequences*** (with soils arranged according to changes in relief).

Soil Catenas. As one moves downslope in a particular landscape, the soils often interact with water and the water table in a systematic, predictable way that defines a **catena** of soils (see Section 2.6). The catena concept is similar to that of a toposequence, except that in a catena the member soils may or may not share a common parent material. A catena of soils usually consist of a well-drained member near the slope summit, sometimes an excessively drained member on the shoulder slope, a moderately well-drained member near the toe slope, and somewhat to very poorly drained members at the bottom. The concept of a soil catena is

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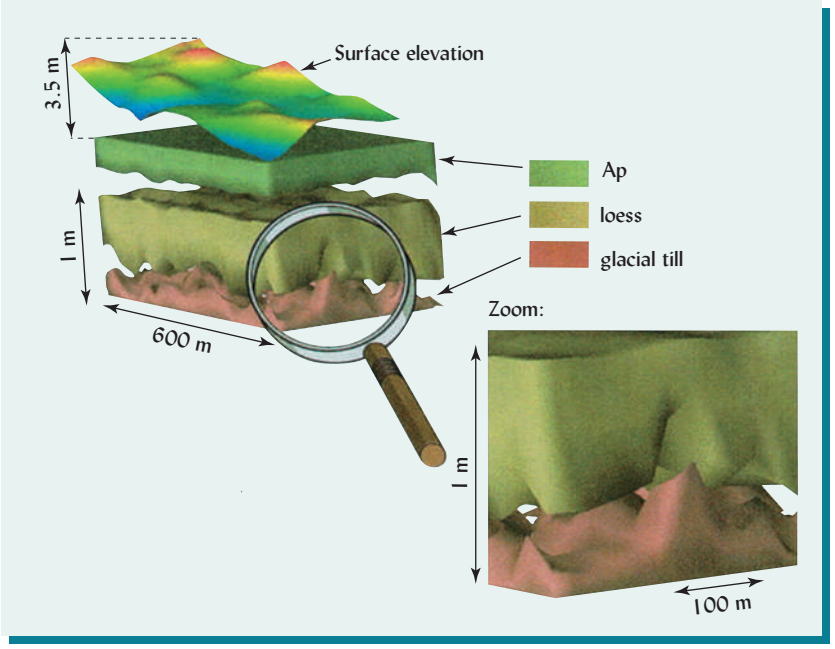

Figure 19.3 *Three-dimensional model of a small area in a Mollisols landscape (about 600 × 400 m) in southern Wisconsin, USA. The three layers are separated in the model to emphasize the variability in the thickness and boundaries of the horizons. The Ap horizon and two layers of underlying glacial parent materials (loess and glacial till) are depicted. The topmost layer represents the surface topography of the land as a kind of 3D contour map showing several small knolls. The surface contours were generated from data in a digital elevation model (DEM) database. The double headed arrows indicate the different scales used in different parts of the model.* [Modified from Grunwald et al. (2000)]

helpful in relating the soils to the landscape in a given region. The various soils in a catena can often be distinguished by the colors of the surface soil, and even more clearly by the colors of the B horizons. For example, in the tropical catena shown in Figure 2.34, the colors vary from dark gray at the bottom of the slope to dusky red at the top.

The relationship can also be seen by referring to Figure 19.4, illustrating the Bath–Mardin–Volusia–Alden catena. Although all four or five members of the catena are not always found together in a given area, the diagram illustrates the spatial relationship among the soils with respect to their drainage status and slope position. As shown, the drainage status of each catena member gives rise to distinct profile characteristics that affect plant rooting depth, species adaptation, and engineering uses of the soils.

Although in different regions catenas may be characterized by different features, several trends are commonly observed moving from upslope to downslope positions, the changes being more pronounced in humid than in dry regions. Because of the relationship to the groundwater and the anaerobic conditions that accompany waterlogging, the chroma of the subsurface soil colors tends to be lower in downslope soils, and iron depletions or other redoximorphic features become increasingly numerous, more pronounced, and occur closer to the soil surface. In addition, the A horizons usually increase in thickness and darken in color due to denser vegetation and slower decomposition in the wetter soils (see Section 12.8), and deposition of organic-enriched surface material eroded from upslope soils (see Section 17.3). The texture of the surface horizon is also likely to differ across a catena of soils. For example, in deep loess, erosion may preferentially move the silt and clay fractions downhill, leaving sandier material on the summit and shoulder and depositing silt and clay in the lower positions. On the other hand, in catenas with well-developed argillic horizons, the upper catena members may have the finer-textured surfaces because erosion has removed most of their coarse-textured A and E horizons, exposing the clayey material from the B horizons.

Soil Associations. A **soil association** is a more general grouping of individual soils that occur together in a landscape. Soil associations are named after the two or three dominant soils in the group, but may contain several additional, less extensive soils. The soils may be from the same soil order or they may be from different orders (Figure 19.5*a*,*b*). They may have formed in the same or in different parent materials. The only requirement is that the soils occur together in the same area. Identifying soil associations is of practical importance, because they enable us to model or characterize landscapes across large areas and they assist

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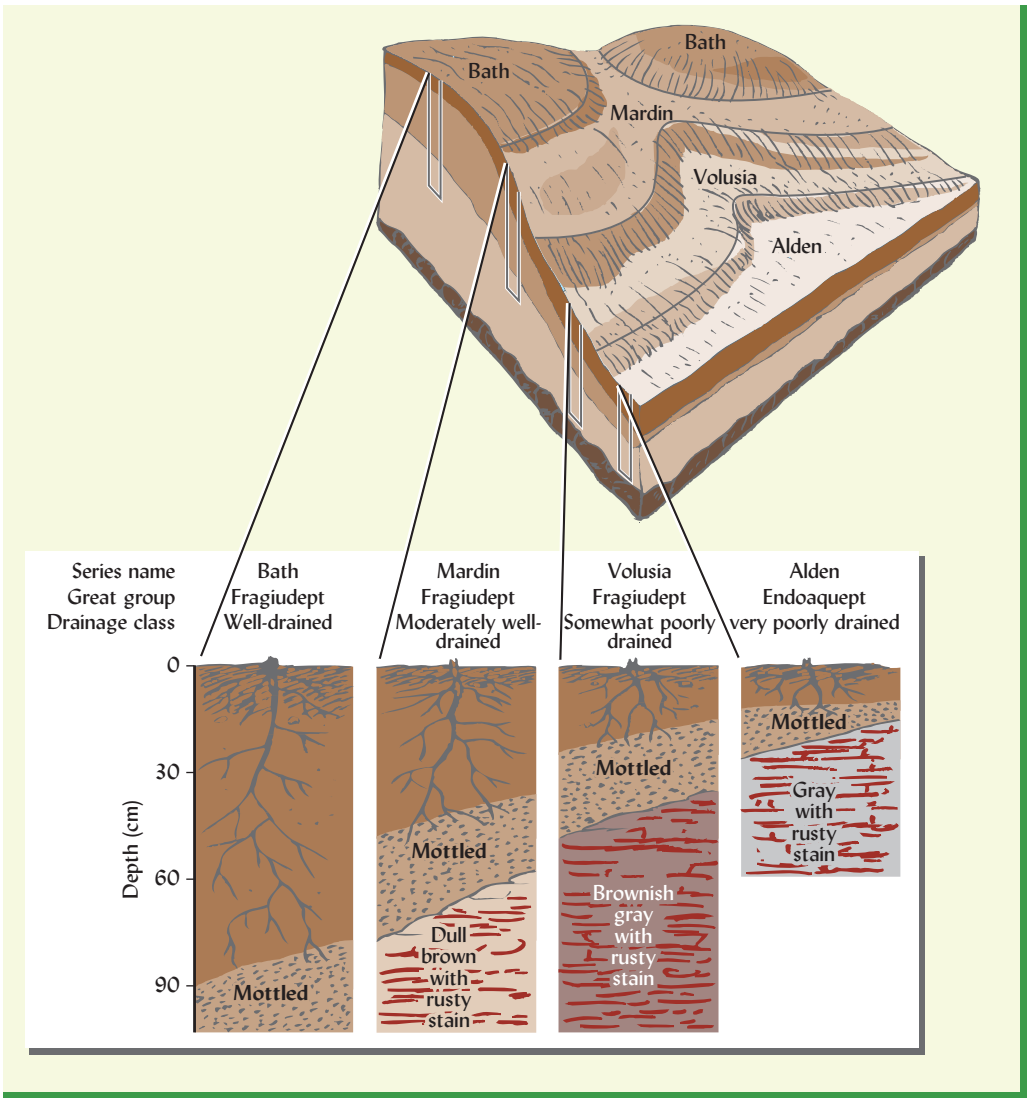

Figure 19.4 *Profile monoliths of four soils of a drainage catena* (below) *and a block diagram showing their topographic association in a landscape* (above). *Note the decrease in the depth of the well-aerated zone (above the mottled layers) from the Bath (well-drained, upslope) to the Alden (poorly drained, downslope). The Alden soil remains wet throughout the growing season. These soils are all developed from the same parent material and differ only in drainage and topography. All four soils belong to the Inceptisols order.* (Based on Cline and Marshall (1977))

in planning general patterns of land use. A given soil association models a defined range of soil properties and landscape relationships, even though the range of conditions included may be quite large (see Figure 19.5*b*).

Large-Scale Soil Variability

At a very large scale, soil patterns are principally the result of climate and vegetation patterns and secondarily related to parent material differences. Although it is often useful to refer

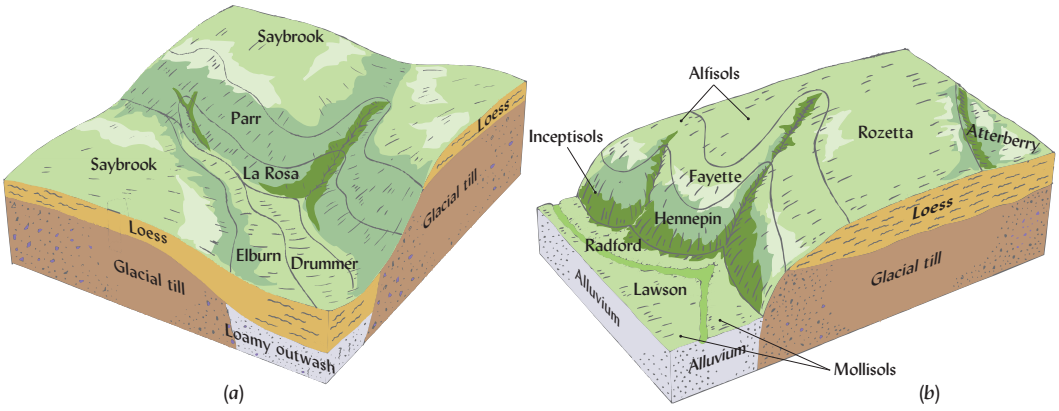

Figure 19.5 *Two soil associations from Bureau County in Illinois, USA. The soils of the Saybrook-Parr-La Rosa association* (a) *are all Mollisols. They differ principally with regard to topography and parent material (Parr and La Rosa developed in glacial till, the others mainly in loess). The Rozetta-Fayette-Hennepin association* (b) *includes a wider range of soil conditions and includes soils from three soil orders.* (Based on Zwicker (1992))

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to general regional soil characteristics, it must be remembered that much localized variation exists within each regional grouping. A study of the World Soils Map printed on the frontpapers of this textbook will reveal important regional patterns. These patterns are also highlighted in the series of small soil-order maps shown in Chapter 3. From these maps it can be seen that highly weathered Oxisols are found principally in the hot, humid regions of South America and Africa drained by the Amazon and Congo rivers, respectively. Mollisols can be seen to characterize the semiarid grasslands of the world; Aridisols are located in the desert regions. The great expanse of loess deposits in the central United States (see Figure 2.16) is an example of the regional influence of parent materials. Soils information on this scale can make an important contribution to inventorying the natural resources of a region or nation, especially if the information includes quantitative data on soil properties (see Section 19.8).

19.2 TECHNIQUES AND TOOLS FOR MAPPING SOILS[1]

Geographic information about soils is often best communicated to land managers by means of a soil map. Soil maps are in great demand as tools for practical land planning and management. Many soil scientists therefore specialize in mapping soils. Before beginning the actual mapping process, a soil scientist must learn as much as possible about the soils, geology, landforms, and vegetation in the survey area. Therefore, the first step in mapping soils is to collect and study older or smaller-scale soil maps, air photo or satellite imagery, geological and topographic maps, previous soil descriptions, and any other information available on the area. Once the soil survey begins, the soil scientist's task is threefold: (1) to define each soil unit to be mapped (see Section 19.3); (2) to compile information about the nature of each soil; and (3) to delineate the boundaries where each soil unit occurs in the landscape. We will now discuss some of the procedures and tools that soil scientists use to map soils in the field.

Soil Description[2]

Soil scientists may use computers and satellites, and as technology continues to advance, these tools become more relevant to soil scientists, but spades and augers remain critically important. Despite technological advances of recent years, the heart of soil mapping still lies in the soil pit (Figure 19.6). A soil pit, whether dug by hand or with a backhoe, is basically a rectangular hole large enough and deep enough to allow one or more people to enter and study a typical pedon (see Section 3.1) as exposed on the pit face. Figures 2.29, 3.12, 3.16, 3.20, and 3.38 are examples of photographs taken of such pit faces. Before describing a profile, it is necessary to clean away the surface material from the pit face to expose fresh soil at all depths. This is done using a sturdy knife or trowel, starting at the ground surface (top of the pit wall) and working down such that the last layer to be cleaned is at the pit bottom. In this way, the soil removed will not fall onto and obscure the previously cleaned layers. In sandy soils this step can be accomplished by making smooth vertical cuts about 2 cm in from the exposed pit face. However, in finer-textured soils with significant structure, individual structural peds should be picked out with a knife point to leave a vertical pit face that follows ped surfaces (e.g. extreme right in Figure 19.6).

The soil scientist then examines the fresh pit face for colors (using a Munsell color book, Figure 4.1), texture (by feel, Figure 4.15), consistency (Table 4.9), structure (Figure 4.21), and plant rooting patterns. Based on these and other soil features, the next step is to determine which horizons are present and at what depths their boundaries occur. Sometimes field kits

[1]For an internationally oriented guide to all aspects of the process of making soil maps, see Legros (2006). For official procedures for making soil surveys in the United States, see USDA-NRCS (2006).

[2]Several detailed practical guides are available and should be consulted to standardize the process of making soil descriptions globally and in the United States (FAO, 2006; Schoeneberger et al., 2012).

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Figure 19.6 *A soil pit allows detailed observations to be made of the soil in place. Here, two soil scientists describe a typical pedon for a mapping unit (Pamunkey soil series) as revealed on the wall of a soil pit. The soil scientists are comparing the colors and textures of soil samples removed from several horizons and recording the observations in a notebook to make a soil profile description (such as the one in Table 19.1). Later, when the soil scientists are boring transects of auger holes to map soils in a landscape (see Figures 19.7 and 19.8), they can determine the identity of the soils they encounter by comparing the properties of samples brought up in their augers to the properties listed in detailed written descriptions of the soil pit.* (Photo courtesy of Ray R. Weil)

are used to perform chemical tests such as pH (Figure 9.11), reduced iron (pink color from α,α-dipyridyl solution), and free carbonates (effervescence from application of 10% hydrochloric acid). Often the estimated horizon boundaries are etched with a knife blade, as can be seen on the right side of Figure 3.43.

A soil description is then written in a standard format (see Table 19.1 for an example) that facilitates communication with other soil scientists and comparison with other soils. As far as possible at this stage, the soil horizons are given master (A, E, B, etc.) and subhorizon (2Bt, Ap, etc.) designations (see Table 2.6). Finally, samples of soil material are obtained from each horizon. These will be used for detailed laboratory analyses and for archiving. The laboratory analyses will provide information for the chemical, physical, and mineralogical characterization of each soil.

Using these techniques, the soil scientists assigned to map an area will familiarize themselves with the soils they expect to find, learning certain unique characteristics that they can look for to quickly identify each soil and distinguish it from other soils in the area.

Delineating Soil Boundaries

For obvious reasons, a soil scientist cannot dig pits at very many locations on the landscape to determine which soils are present and their boundaries. Instead, he or she will bring up soil material from numerous small boreholes made with a hand auger or hydraulic probe (Figure 19.7*a*,*b*). The texture, color, and other properties of the soil material from various depths can be compared mentally to characteristics of the known soils in the region.

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Table 19.1
SOIL PROFILE DESCRIPTION FOR THE THORNDALE SOIL SERIES[a]

Horizon designation	Diagnostic horizon	Horizon boundaries	Description of horizon in typical pedon
Ap	Ochric Epipedon	0–20 cm	Dark grayish brown (2.5Y 4/2) silt loam; weak medium granular structure; friable, slightly sticky, slightly plastic; many fine roots; neutral; clear smooth boundary.
Btg1	Argillic horizon	20–43 cm	Light olive gray (5Y 6/2) silty clay loam; moderate coarse subangular blocky structure; slightly firm, sticky, plastic; few medium and fine roots; many prominent dark grayish brown (10YR 4/2) clay films on faces of peds; common medium prominent reddish brown (5YR 4/3) masses of iron accumulations; slightly acid; clear smooth boundary.
Btg2	Argillic horizon	43–65 cm	Light olive gray (5Y 6/2) silty clay loam; weak coarse prismatic structure parting to moderate medium subangular blocky; firm, sticky, plastic; few fine roots; many prominent dark grayish brown (10YR 4/2) clay films on prisms and faces of peds; common medium and fine prominent reddish brown (5YR 4/4) masses of iron accumulations in the matrix; slightly acid; gradual smooth boundary.
Btxg	Argillic horizon; Fragipan	65–103 cm	Grayish brown (10YR 5/2) silty clay loam; weak very coarse prismatic structure parting to weak medium subangular blocky; firm, brittle, moderately sticky, moderately plastic; few fine roots; many faint dark grayish brown (10YR 4/2) clay films on prism faces and few faint dark grayish brown (10YR 4/2) clay films on faces of peds; common fine to medium prominent reddish brown (5YR 4/4) and brown (7.5YR 5/4) masses of iron accumulations in the matrix; slightly acid; abrupt smooth boundary.
C		103–163 cm	Strong brown (7.5YR 5/6) and reddish yellow (7.5YR 7/6) silt loam; massive; friable, slightly sticky, slightly plastic; common medium prominent grayish brown (2.5Y 5/2) iron depletions in the matrix; slightly acid.

[a]Thorndale soils are very deep, poorly drained soils formed in medium-textured colluvium derived from limestone, calcareous shale, and siltstone. Slopes are 0–8%. Permeability is slow. Mean annual precipitation and temperature are about 100 cm and 12 °C. Taxonomic class is fine-silty, mixed, active, mesic Typic Fragiaqualfs.
Adapted from official series description (USDA/NRCS, 2015b).

With hundreds of different soils in many regions, this might seem to be a hopeless task. However, the job is not as daunting as one might suppose, for the soil scientist is not blindly or randomly boring holes. Rather, he or she is working with a landscape model in mind—an understanding of the soil associations and how the five soil-forming factors determine which soils are likely to be found in which landscape positions.

Usually there are only a few soils likely to occupy a particular location, so only a few characteristics must be checked. The soil auger is used primarily to confirm that the type of soil predicted to occur in a particular landscape position is the type actually there. The nature of soil units and the locations of the boundary lines surrounding them are inferred from auger borings at numerous locations across a landscape. A simple but laborious and time-consuming approach to obtaining such spatial information on soils is to make auger borings at regular intervals (say, every 50 m) in a grid pattern across the landscape (Figure 19.8*a*). Points with similar properties can then be connected to form soil boundaries. This approach is sometimes used in countries where labor to survey the sampling points and auger the soils is quite inexpensive and information to build landscape models is quite limited.

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Figure 19.7 *Soil maps are prepared by soil scientists who examine the soils in the field using such tools as a truck-mounted hydraulic soil probe* (a) *or a hand-powered soil bucket auger* (b). *About a 10-cm depth increment of soil is typically retrieved with just two or three revolutions of the typical bucket auger. After pulling the auger from the ground, but before emptying its load of soil, it is advisable to carefully examine the soil exposed at the end of the auger bucket to observe the relatively undisturbed colors and structure of the soil* (c,d). *Soil scientists may lay each soil increment in order on a sheet of plastic or in a trough to examine later* (e). *This allows the colors and textures to be efficiently determined while also presenting an overall view of the soil profile.* (Photo (a) courtesy of USDA/NRCS, other photos courtesy of Ray R. Weil)

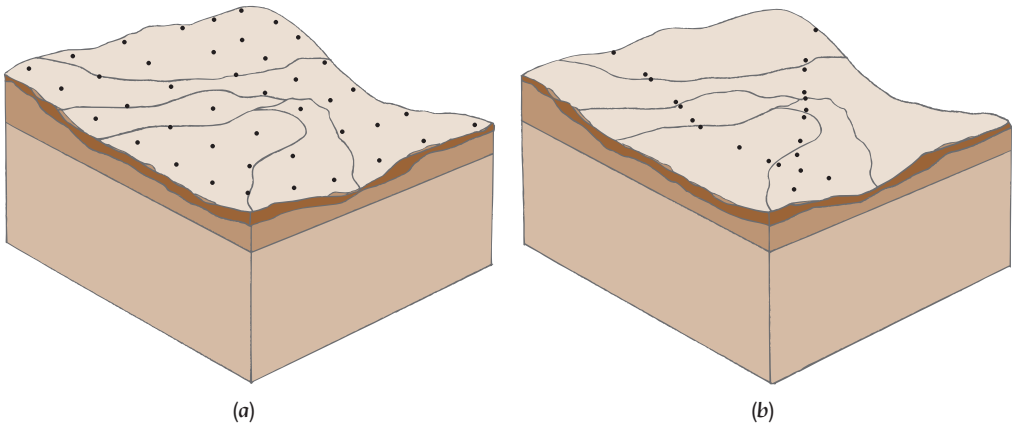

Figure 19.8 *Two approaches to collecting information on soil properties and boundaries by soil auger borings (indicated by dots). The regularly spaced grid pattern* (a) *of borings is simple in concept, but very labor-intensive to carry out. In a much more efficient approach* (b), *the soil scientist traverses the landscape along selected transects (straight-line paths), augering only at enough points to confirm soil properties and boundaries predicted on the basis of soil–landscape relationships. Note that in order to pinpoint soil boundaries, extra borings are made near the places these boundaries are expected to occur.* (Diagram courtesy of Ray R. Weil)

A landscape model that reflects knowledge of the interplay of the soil-forming factors across the land can greatly expedite the soil scientist's work. An efficient soil mapper will select sites to make auger borings based on information obtained from detailed maps or imagery of topography, vegetation, and drainage networks, as well as from observed changes in topography, vegetation, and soil surface colors. A typical approach is to traverse the landscape along selected transects (straight-line paths), augering only at enough points to confirm expected soil properties and boundaries. In order to better more accurately locate soil boundaries, more frequent borings are made near the places where breaks in slope or other landscape clues suggest that soil boundaries will occur (see Figure 19.8*b*). Although soil boundaries are drawn on soil maps as sharp lines, we know that soil properties (thickness of horizons, colors, textures, etc.) change gradually across a landscape. In this regard different soils are somewhat like different colors. For example, green and yellow are definitely two

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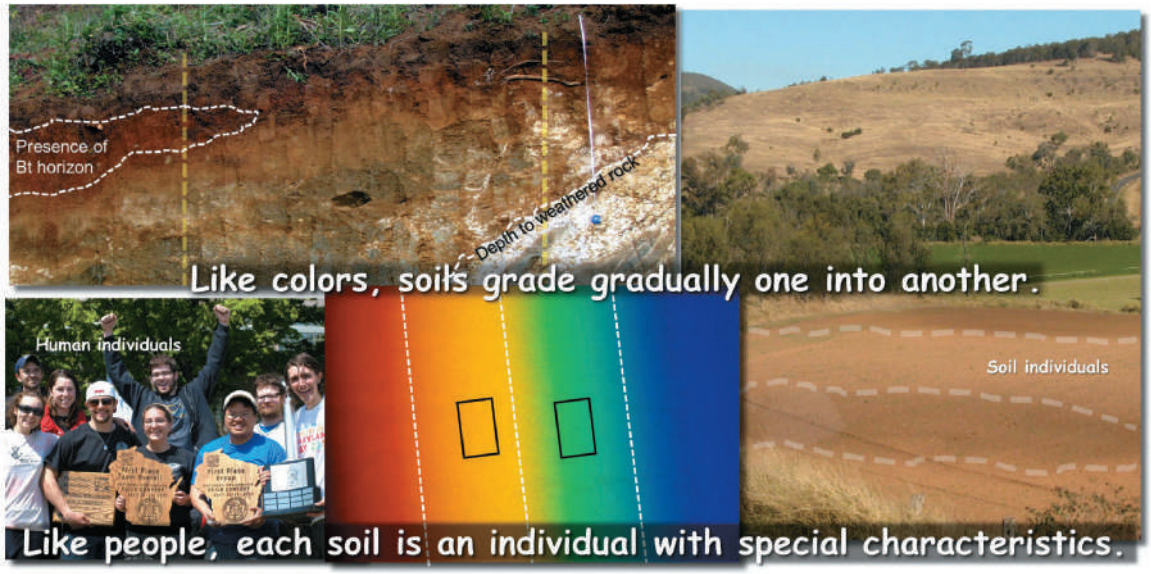

Figure 19.9 *Like individual people, each soil is different. However. soil properties (thickness of horizons, colors, textures, etc.) vary more or less gradually across a landscape. Therefore soils change gradually from one individual into another, despite the fact that soil maps represent soil boundaries as definite lines. In this regard different soils are somewhat like different colors. Green and yellow are definitely two different colors, but the boundary between them on the spectrum is defined rather arbitrarily.* (Group photo of the U.S. national championship soil judging team, courtesy of Karen Vaughan, California Polytechnic State University; other photos courtesy of Ray R. Weil)

different colors, but the boundary between them on the spectrum is rather arbitrarily defined (Figure 19.9).

In Figure 19.10, a soils map made using transect borings, *left*, is compared to an aerial photo of the bare cultivated soil in the same area. The figure also compares these to a map of one surface soil property derived from measurements on a large number of samples taken in a grid pattern covering the same area.

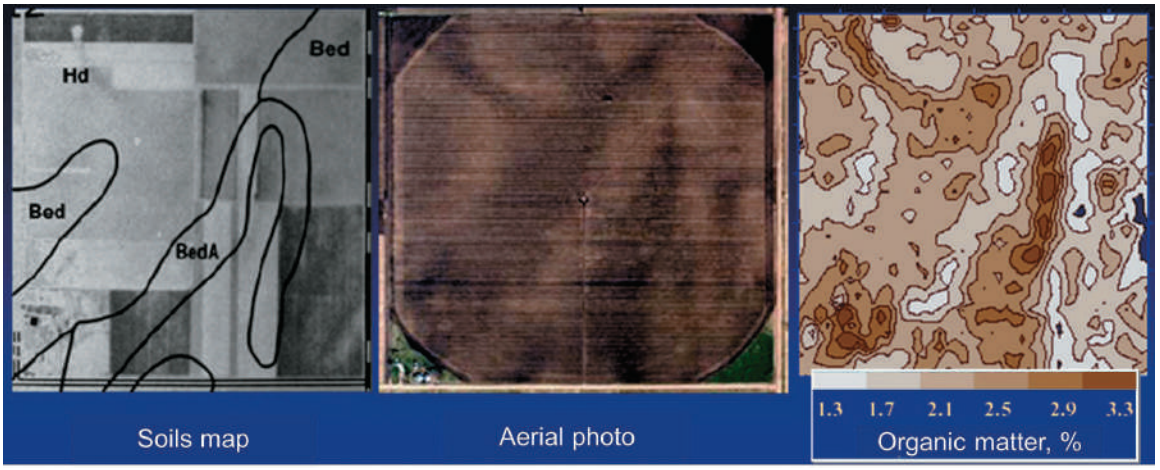

Figure 19.10 *Soil variability in 2.5 km^2 of farmland.* (Left) *The area as represented in the soil survey map delineating six mapping units (and two soil series). The black-and-white air photo background was taken while crops covered all but the three dark-colored fields (where the bare soil can be seen).* (Middle) *An air photo taken some years after the land was converted to center pivot irrigation (Section 6.9) and the many rectangular fields were combined into one large, rounded field. The soil has just been plowed and variations in soil color (mainly related to the effect of topography on organic matter content) are easily distinguished.* (Right) *Spatial distribution of surface soil organic matter content (ranging from 1.3% to 3.3%) presented on a map created from analysis of many soil samples obtained in a grid pattern across the entire area. The spatial correlation between the soil organic matter data* (right) *and the soil colors* (middle) *is very close. The delineation of soil mapping units* (left) *also approximates the organic matter/drainage differences, the mapping units in the swales coded as "Hd" being higher in soil organic matter than the mapping units on the hills coded as "Bed."* (Images courtesy of USDA/ARS Agroecosystems Management Unit, Nebraska)

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Figure 19.11 *A block diagram* (left) *of the soils and surficial geology of Washington, DC, USA, near the national mall, an area also seen in the oblique air photo* (right). *Block diagrams can represent the spatial arrangement of landscape elements including soil series, landforms, and underlying parent materials. Soil scientists often observe geologic layers, but in soil surveys they usually describe only the surface layers to a depth of about 2 m. Block diagrams can be used to associate information on substrata with the surface soil mapping units to help land users understand and manage both soils and underlying parent materials.* (Diagram courtesy of USDA/NRCS; photo courtesy of Ray R. Weil)

Soil mappers often visualize a landscape model by drawing a block diagram, which provides a stylized depiction of the main landforms and associated soils. A block diagram can communicate a deeper understanding of the existing landscape and aid in engineering applications if it accurately depicts the underlying substrata (parent materials, C and R horizons) as well as the A and B horizons on which most soil classification is focused. Figure 19.11 illustrates such a diagram for an urban area in Washington, DC, USA.

19.3 MODERN TECHNOLOGY FOR SOIL INVESTIGATIONS

Global Positioning Systems[3]

An obvious prerequisite for delineating the location of soil bodies in the field is that the soil mappers know their location as they traverse a landscape. Traditionally, soil mappers have used large-scale base maps, air photos (see Section 19.5), and a compass to ascertain location. However, in nearly featureless terrain or heavily vegetated areas these aids are of limited use. Fortunately, soil mappers can now take advantage of Global Positioning System (GPS) technology to identify precise locations anywhere in the world (Box 19.1).

This technology can be applied in making soil maps, allowing the soil scientist in the field to record the precise geographic coordinates of each soil observation made. The soil information mapped may be the name of the taxonomic map unit (as for soil surveys) or it may be a measured soil property, such as the organic matter content or nutrient availability index. In the latter case, special maps can be prepared by *geostatistical* computer programs that estimate values for the soil property in question at all points between the points actually sampled (see Sections 19.8 and 19.10). Therefore, GPS is an integral part of modern instrumental systems for investigating soils in the landscape.

While it is still the mainstay of soil investigations and mapping, soil augering is intrusive (i.e., it makes holes) and labor-intensive. Several nonintrusive methods of soil investigation are finding increasing use. These technologies include: (1) ground-penetrating radar (GPR),

[3]For a readable discussion of the principles behind the GPS, see Herring (1996).

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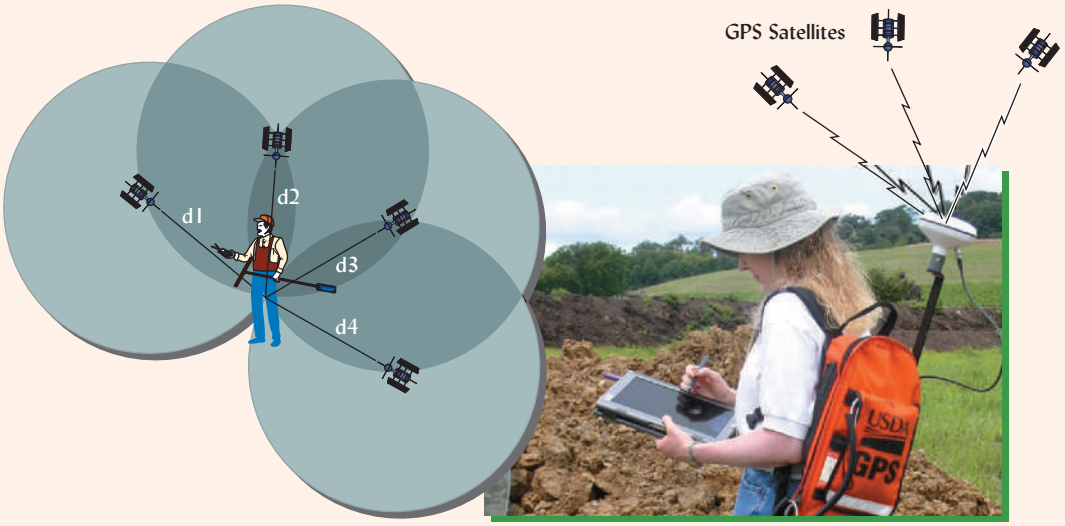
BOX 19.1

USING THE GLOBAL POSITIONING SYSTEM TO MAP SOILS INFORMATION

A network of several dozen GPS satellites was developed by the U.S. Defense Department to aid in the navigation of military planes and ships during the 1980s. The system can now be used by civilians almost anywhere in the world to determine their precise location almost instantaneously. The GPS satellites are orbiting some 20,000 km above the Earth in precise patterns so that at least four satellites are broadcasting simultaneously to any point on Earth's surface. The group of satellites in communication with a GPS receiver is called the *satellite constellation*.

An electronic clock in the receiver measures how long it takes for a pattern of radio signals to travel to it from each satellite. Given that the signals travel at the velocity of light, the receiver can calculate the distance to each satellite (distance = velocity × time). A receiver located at, say, 20,200 km from a particular satellite must be located someplace on the surface of an imaginary sphere that has its center at the satellite transmitter and has a diameter of 20,200 km. If the same receiver is also located at 20,700 km from a second satellite, it must also be located someplace along the surface of a second sphere 20,700 km in diameter. Simple geometry tells us that four such spheres can intersect at only one point in space (Figure 19.12, *left*), that point being the exact location of the receiver.

Because the setting of the satellite clock may not be known exactly, accuracy is not always optimal. One corrective measure involves installing a stationary receiver at an exactly known location on a tall building or tower. Mobile receivers then use broadcasts from the stationary receiver to calculate the "errors" in each satellite clock. Other *differential correction* signals are available from government and commercial sources broadcasting from FM radio and cellphone towers. Without these corrections, simple, handheld receivers can determine locations to within 2–6 m. With these corrective measures in use, even relatively small and inexpensive GPS receivers can determine locations to within 1–3 m, and larger, more sophisticated receivers (Figure 19.12, *right*) can determine locations to within a few centimeters.



(*a*) (*b*)

Figure 19.12 *The Global Positioning System of satellites and receivers.* (Left) *A GPS receiver uses radio signals to determine its distance (d1, d2, etc.) from each of at least four orbiting satellites. The spheres of distance around the individual satellites intersect at only one position in space, the location of the receiver.* (Right) *Soil mapping in the field using a computer tablet to record observed soil properties and a backpack GPS receiver to geo-reference the location of each observation. Three of the satellites in contact with the GPS receiver are schematically illustrated. The computerized GPS system can also be used to guide the mapper to a set of predetermined soil sampling locations.* (Diagram and photo courtesy of Ray R. Weil)

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(2) electromagnetic (EM) induction, (3) apparent electrical conductivity, and (4) light reflectance spectroscopy (especially in the visible and near infrared range of the light spectrum).

Ground-Penetrating Radar

GPR can be used to investigate subsurface layers while increasing the quality and reducing the cost of making soil maps. GPR is a noninvasive geophysical tool (no digging is required) that can produce images of contrasting layers in the upper regolith (0–30 m). The GPR transmits oscillating waves of electromagnetic energy that move through the soil until they hit a contrasting layer which reflects back some of the energy. This reflected energy is measured and displayed on a radar record as the instrument is pulled across the land surface (Figure 19.13*a*). The amount of energy reflected depends on the degree of contrast in dielectric permittivity of the two adjoining layers. The dielectric permittivity of different soil layers is a property largely determined by the moisture content, salinity, and density of the material. For example, in many soils, a subsurface clay accumulation (Bt horizon) is more dense and moist than the layers above it and so causes an identifiable reflection front that allows the upper boundary of this subsoil horizon to be seen in the radar record (Figure 19.13*b*). In sandy soils, the water table produces strong reflections on the radar record, making it easy to map the depth to the water table (Figure 19.13*c*). The vertical scale on the record actually shows the time (in nanoseconds, ns) it took for the energy pulse to travel down to the reflecting layer and back to the instrument. Calibrating the instrument for the particular type of soil material encountered determines the velocity (between about 3 and 20 m/ns) at which the energy traverses the material,

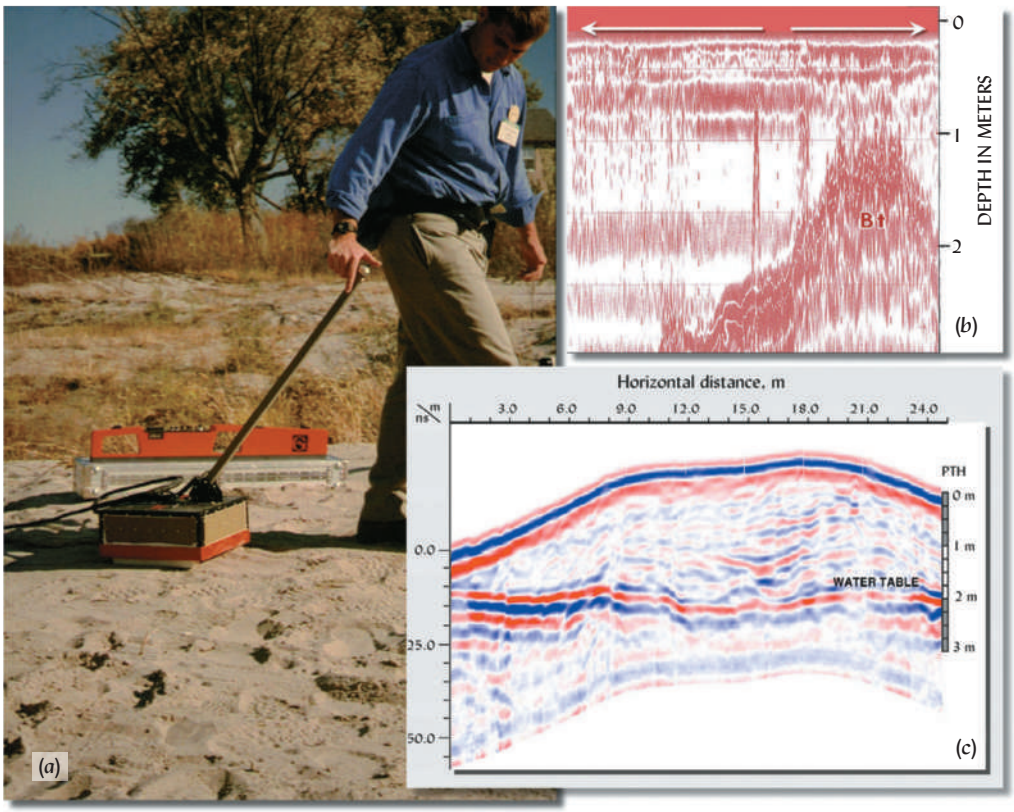

Figure 19.13 *Use of ground-penetrating radar (GPR) to investigate the depth to contrast subsurface layers.* (a) *As the GPR instrument is pulled over the soil surface, it emits an oscillating radar signal that penetrates the soil to as much as 30 m depth under favorable conditions.* (b) *An example of a radar record output from a GPR instrument, showing the depth to the Bt horizon in two Florida soils. The GPR signals are sensitive to the dramatic change in soil properties between the coarse sands of the upper horizons and the clay enriched Bt horizon. On the left side of the graph are the deep sands of the Chandler soil, a Quartzipsamment without an argillic horizon in the upper 2 m. On the right side of the graph, the Bt horizon of an Apopka soil (a Paleudult) can be clearly seen. The boundary between the two soils is gradual, but could be delineated as indicated by the two arrows at the top of the graph. The distance across the entire graph is about 140 m.* (c) *In sandy soils, GPR can be used to chart the depth to the groundwater table.* [Photo courtesy of Ray R. Weil; graphs modified from Doolittle (1987) and Doolittle et al. (2006)]

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allowing the vertical scale on the radar record to be expressed as depth (m) rather than travel times (ns). Figure 19.13*c* shows the two-dimensional radar record from a single pass (transect) of the GPR. If many parallel transects are made the resulting records can be statistically combined into a three-dimensional map of the groundwater surface, enabling the investigator to predict the direction and rate of groundwater flow. Such a map provides an invaluable resource for investigating the movement of pollutants. The GPR is not suitable for all soils, because the combination of moisture, salt content, and type of clay may make the reflectance record difficult to interpret. Where it is effective, however, the cost of GPR is only about one-third that of detecting soil or groundwater boundaries by making multiple borings with a soil auger.

Electromagnetic Induction and Apparent Electrical Conductivity

EM induction techniques offer another noninvasive, rapid method of investigating subsurface features. Using a handheld instrument approximately the size and shape of a carpenter's level (red instrument in background Figure 19.13*a* and in Figure 10.19), this method measures the apparent conductivity of the soil for electromagnetic energy. Other instruments involve electrodes that penetrate the soil, including some models in which the electrodes are rolling discs that cut into the soil as they are pulled across the landscape (Figure 19.14).

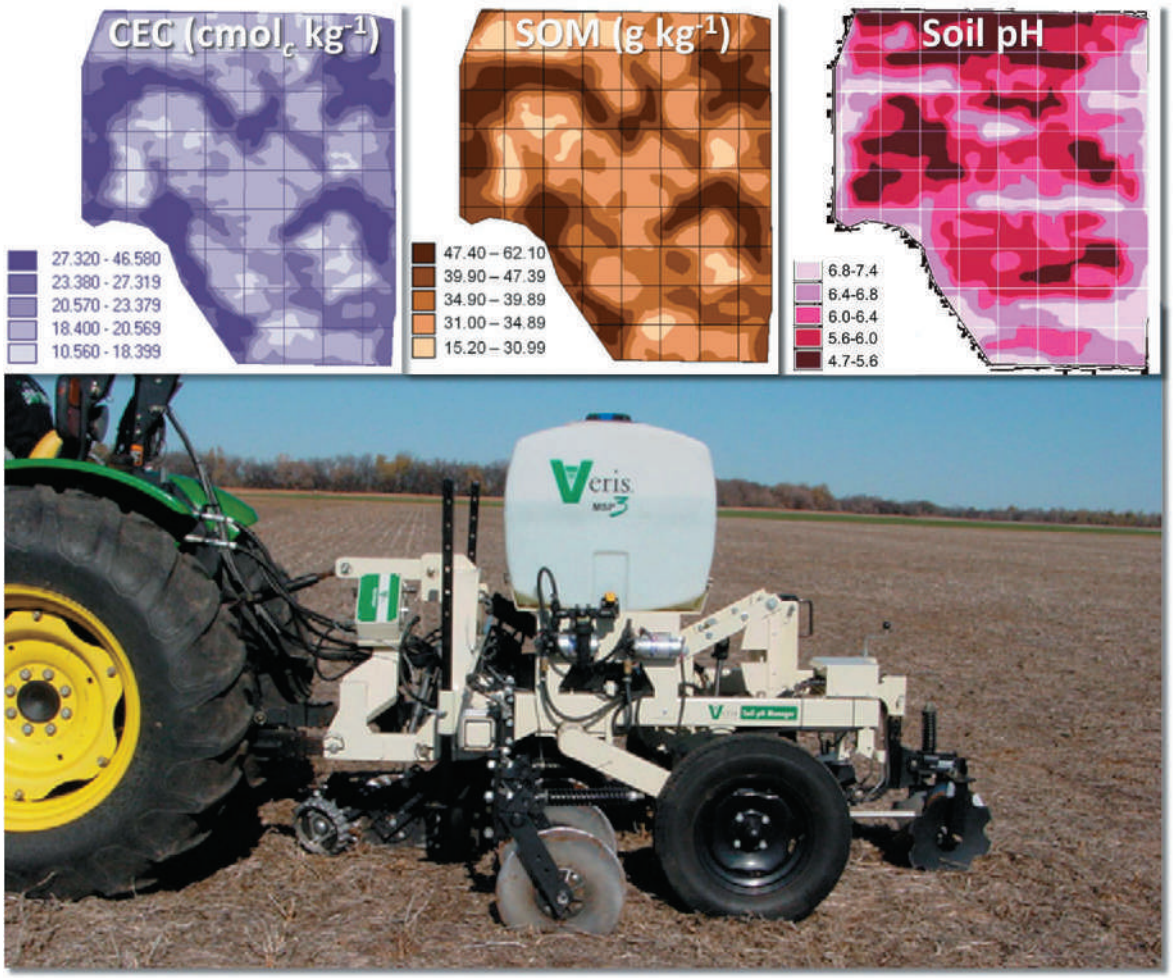

Figure 19.14 *Maps of soil cation exchange capacity (CEC), soil organic matter (SOM), and soil pH made from data collected by on-the-go sensing systems pulled across a large agricultural field. The straight lines on the maps delineate 1 ha grids. The advantage of continuous on-the-go sensing over grid soil sampling can be seen by the range of pH values within a single grid cell. The sensing equipment used (photo) included shallow and deep apparent soil electrical conductivity (ECa) and red and near infra-red (NIR) reflectance spectrometers. The sensed data were highly correlated with both OM and CEC, thus very similar spatial patterns were found for these two soil properties.* [Modified from Kweon (2012)]

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The conductivity measured by these instruments can be related to the moisture content, salinity of the soil (see Section 10.4), and the amount and type of clays in the soil. This technique has been successfully used to map out the depth and thickness of claypan horizons in humid regions and to investigate groundwater contamination and salinity in arid regions (see Figure 10.20).

Conductivity sensors can be combined with other sensing instruments to get a more complex and complete picture of the soil. When data from the instruments are compared to lab measurements made on soil samples from the same area, computer models can relate the sensed signals to variations in soil properties and generate surprisingly detailed maps (Figure 19.14).

Direct Sensing of Soil Properties by Reflectance Spectroscopy[4]

Certain properties of the upper 2–20 mm of soil alter the manner in which the soil surface reflects various wavelengths of radiant energy (see Figure 19.15). The reflected energy can be scanned over the near infrared radiation spectra (wavelengths in the range of about 700–2500 nm) using a special monochromator instrument. At these wavelengths, each part of a complex soil organic or mineral substance produces a special absorption pattern related to particular vibrations caused by stretching and bending of molecular bonds (see Figure 19.16 for spectra typical of three different clay minerals). Depending on the wavelengths being monitored, a number of soil properties can be directly sensed and recorded. Direct sensing of soil properties usually requires a sensor tuned in to specific bands of wavelengths and a computer program designed to interpret the complex data using sophisticated statistical manipulation and correlations. Soil properties that have been successfully estimated by such spectral sensing include the soil contents of clay, sand, organic matter, water, iron oxide, copper, zinc, titanium, nitrogen, and phosphorus as well as albedo (overall reflectivity), temperature, cation exchange capacity, salinity, and soil structure.

New uses for near infrared spectroscopy are being rapidly developed. Variations of the technology have been developed that allow rapid determination of many soil properties in the lab or on the ground. Soil samples in the laboratory can now be analyzed for numerous nutrients and constituents without having to perform time-consuming and pollutant-generating wet chemistry procedures. Portable reflectance systems are being developed that can sense changes in soil organic matter, texture, or water content "on the go"—that is, as the instrument is being pulled by a tractor through the surface soil across a landscape. Such technologies promise to revolutionize not only soil mapping, but also the fields of soil testing (Section 16.11) and precision farming (see Section 19.10). It should be noted that most of these electronic methods of soil investigation must still be adapted to each situation by the user. Initial calibrations are necessary to quantify the relationship between the soil properties of interest and the electronic signals recorded by the instruments. Once calibrated, these technologies can

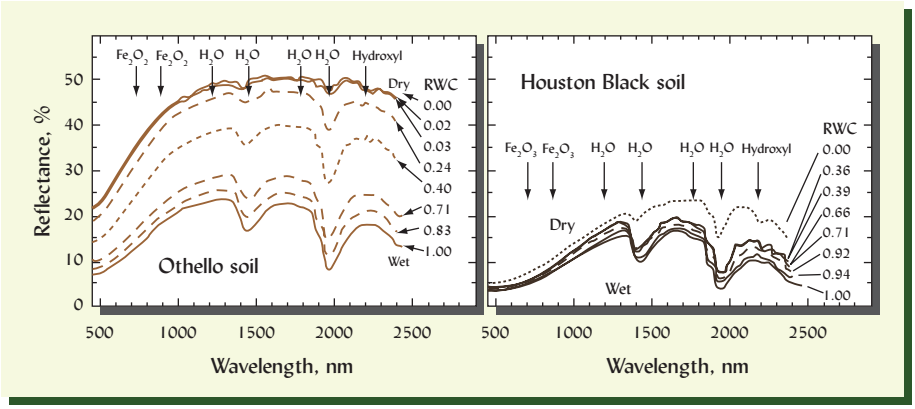

Figure 19.15 *Reflectance spectra of two contrasting soils (Othello, a sandy Ultisol and Houston Black, a clayey Vertisol) at various relative water contents (RWC) ranging from oven dry (RWC = 0.0) to water saturated (RWC = 1.0). High iron content correlates with low reflectance in the two iron oxide (Fe_2O_3) bands. High organic matter correlates with low reflectance in the hydroxyl band. Comparing the dry soils, note the much lower overall reflectance for the Houston Black, which is, as its name suggests, a very black colored soil. Two "valleys" (inverted peaks of low reflectance) caused by water at 1450 and 1950 nm are especially obvious. The clear differences between the two soils and among water contents within a soil suggest how such spectral data can be useful in mapping soils and soil properties. Downward arrows indicate the reflectance wavelength attributed to Fe_2O_3, H_2O, or hydroxyl.* (Modified from Daughtry (2001))

[4]For a review of progress in soil analyses by reflectance spectral methods, see Soriano-Disla et al. (2013).

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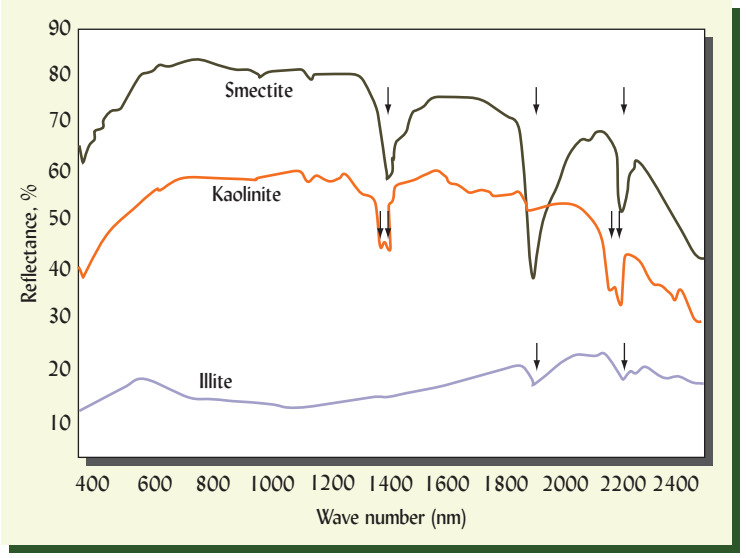

Figure 19.16 *Typical light spectra in the visible and infrared range for three clay minerals important in soils. In a kind of mineral "fingerprint," each mineral exhibits pronounced inverted peaks of low reflectance (arrows) at a combination of wavenumbers characteristic for that mineral.* (Generalized graph courtesy of Ray R. Weil)

provide detailed information about soil properties and subsurface features and can be a great aid in determining the location of soil boundaries on detailed soil maps.

19.4 REMOTE SENSING IN SOIL SURVEY[5]

Remote sensing describes the gathering of information from a distance. In this general sense of the term, we are remote sensing any time we use our eyes to see an object from a distance rather than picking up that object in our hands and feeling it. When we perceive an object, our brains are forming a mental image in response to light energy that has reflected off the object into our eyes. In an analogous manner, a photographic or digital image can be formed by sensors (e.g., cameras) mounted on a platform (e.g., an airplane, unmanned aerial vehicle, or space satellite), providing a suitable vantage point for observing a particular area of land. While our eyes respond only to reflected energy with wavelengths in the visible range, other sensors can form images from additional wavelengths of energy, such as radar or infrared. We will briefly describe several types of imagery and their uses in making geographic soils investigations. Remote sensing imagery of various kinds covering most locations in the world are available from a number of government agencies and private companies. Some of the instruments used in on-the-ground (proximal) soil investigations as discussed in Section 19.3 can also be mounted on flying platforms and used in remote sensing (Table 19.2).

Black-and-White Air Photos

Black-and-white air photos made with panchromatic sensors have been widely used in land management and soil mapping. The film or digital camera sensor "sees" a range of light wavelengths that closely corresponds to the spectrum visible to our eyes. The image produced is black and white or, more correctly, many shades of gray. Gray-shade air photos and aerial digital camera images can reveal a wealth of information about landforms, vegetation, human influences, and, yes, soils. But experience is required to recognize the various gray tones and patterns as different types of vegetation, drainage patterns, and soil bodies.

Other sensors produce such images as natural color or infrared false color and are also used in aerial photography. Infrared images are commonly used by forest managers because conifer needles absorb infrared energy much more completely than do hardwood leaves, allowing the conifers to be easily distinguished by their darker tones on the image.

[5]For an explanation of historical, present, and possible future types of base maps used in soil survey, see Miller and Schaetzl (2014).

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Table 19.2
FEASIBILITY OF USING VARIOUS INSTRUMENTS FOR REMOTE (AERIAL VEHICLE OR SATELLITE), AND PROXIMAL (ON-THE-GROUND) SENSING OF TERRAIN AND SOIL PROPERTIES[a]

	Instruments for remote sensing					Instruments for proximal sensing				
Selected attributes	Passive radar	Active radar	Lidar	Multispectral reflectance	Spectro scopy	Passive radar	Active radar	Lidar	Multispectral reflectance	Spectro scopy
	Feasibility of determination by remote sensing					Feasibility of determination by proximal sensing				
Soil mineralogy	.	.	.	XX	XXX	.	.	.	.	XXXX
Soil texture	.	XX	.	XX	XX	.	XXXX	.	.	XXXX
Soil iron content	.	.	.	X	XX	.	.	.	.	XXX
Soil organic carbon	.	.	.	X	XXXX	.	.	.	.	XXXX
Soil moisture	XXX	XXX	.	XX	X	XXXX	XXXX	.	.	XXXX
Soil salinity	.	XXX	.	X	XX	.	.	.	.	XXX
Soil nitrogen content	.	.	.	.	XX	.	.	.	.	XXXX
Terrain elevation	.	XXXX	XXXX	XX	.	.	.	.	.	.
Terrain slope	.	XXXX	XXXX	XX	.	.	.	.	.	.
Digital soil mapping	.	XXXX	XXX	XXX	XX	.	.	.	.	.
Soil type	.	.	.	XX	XXXX	.	.	.	.	.
Photosynthetic vegetation	.	.	.	XX	XXX	.	.	.	.	.
Land cover	.	X	.	XXX	XXXX	.	.	.	.	.
Land degradation	.	X	.		X	.	.	.	.	.

Key to color-symbol ratings: . = not applicable; X = low; XX = medium; XXX = med. High; XXXX = high

[a]Ratings based on an assessment of published studies in Mulder et al. (2011).

Air photos have been used since 1935 to increase the speed and accuracy of making soil maps. Now often used in digital form, they can assist soil investigations in at least three ways: (1) by providing a base map, (2) as a source of proxy information, and (3) by directly sensing soil properties.

Air Photographs as Base Maps

Detailed (large scale) air photos have been used in the field for nearly a century of soil mapping. Soil scientists can determine their location in the field in relation to such features as buildings, roads, large trees, and streams that are visible on both the photograph and on the ground. Rather than using surveying equipment and a plane table to make a map from blank paper, the soil scientist can draw soil boundaries directly on the air photo. In this way the photograph serves as a *base map*. Review Figure 19.10 (*left*) for an example of a portion of soil map made on an air photo base.

Similarly, topographic maps that show the iso-elevation contours of the land have often been combined with air photos to provide a map base with relief. Although their base map

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function is now usually superseded by GPS location data and digital base map information, air photos (whether digital or on paper) can still provide important information about soils and land.

Map Scales

When using printed air photos or topographic maps, the issue of **map scale** is a very important consideration. Map scales are generally presented as ratios, such as 1:1,000,000 ("one to a million") or 1:12,000 ("one to twelve thousand"). The ratio tells us how many units of length on the ground are represented by one unit of length on the printed map or image. A scale of 1:12,000 is commonly used for detailed soil maps and indicates that 1 cm on the map represents a distance of 12,000 cm (or 120 m) on the ground. The ratio is unitless; therefore, 1 in. on the same map represents 12,000 in. (1000 ft) on the ground. Maps and images are often referred to as being *small scale* or *large scale*, terms that people often find confusing. Let's clear up any confusion about these terms. A *small-scale* map is one with a small *scale ratio* (e.g., 1:5,000,000 = 0.000002), on which a given object, such as a 100-ha lake, occupies only a tiny spot on the map. Small-scale maps show little detail but do cover a large land area. By contrast, a *large-scale* map has a large *scale ratio* (e.g., 1:1000 = 0.001), and a 100-ha lake would occupy a relatively large part of the map. Large-scale maps show lots of detail but represent a small land area.

It should be noted that uncorrected air photos are severely distorted, because the land areas shown near the edges of the photograph were considerably farther from the camera than were the areas directly beneath the passing airplane. Also, in hilly or mountainous terrain the hilltops would have been closer to the camera than the valleys. An ortho photograph is one that has been corrected for both types of distortion. In most paper soil surveys, ortho photographs are used as base maps on which soil boundaries are drawn. Current soil surveys use digital ortho quads, electronic versions of ortho photographs that are compatible with other computerized geographic information (see Section 19.9). However, uncorrected air photos are still used to allow stereoscopic coverage which provide three-dimensionality. The concept is illustrated in Figure 19.17 by two overlapping images of a scene taken from slightly differing vantage points. Try viewing this stereo photo pair in three dimensions!

Air Photos for Proxy Information

Soil investigations are usually concerned with features of soil profiles and other subsurface information. However, air photos record radiant energy reflected off surfaces aboveground or, at most, a few centimeters belowground. Nonetheless, the surface tones (or colors), patterns, and features shown on the photograph often are related to conditions belowground (Figure 19.18). Once you have learned what these relationships are, air photos can be used as a source of *proxy* information about soil conditions.

For example, the photographs do not directly record the depth to the water table; but dark tones indicate moist, high-organic-matter surface soil that may correlate with a seasonally shallow water table. If your mental landscape model (see Section 19.1) suggests that a certain type of soil occurs in the drainageways, then drainageways visible by patterns of dark tones on the photograph serve as a proxy for digging a soil pit or boring an auger hole. Stereo pairs of photographs (Figure 19.17) or topographic base maps can provide a three-dimensional representation of the land surface, and are especially useful in locating drainageways, slope breaks, and other features of relief. The features, in turn, help to locate the soils that are members of known soil associations and drainage catenas.

Vegetation often provides clues about the underlying soils. For example, a certain type of vegetation, recognizable on air photos, may grow only in areas of sodic soils with a natric horizon. The patches of this vegetation seen on the photograph then indicate the locations of the sodic soils.

Drainage patterns visible on air photos (or other topographic base maps) usually reflect the nature of soils and parent materials. For instance, many closely spaced (less than

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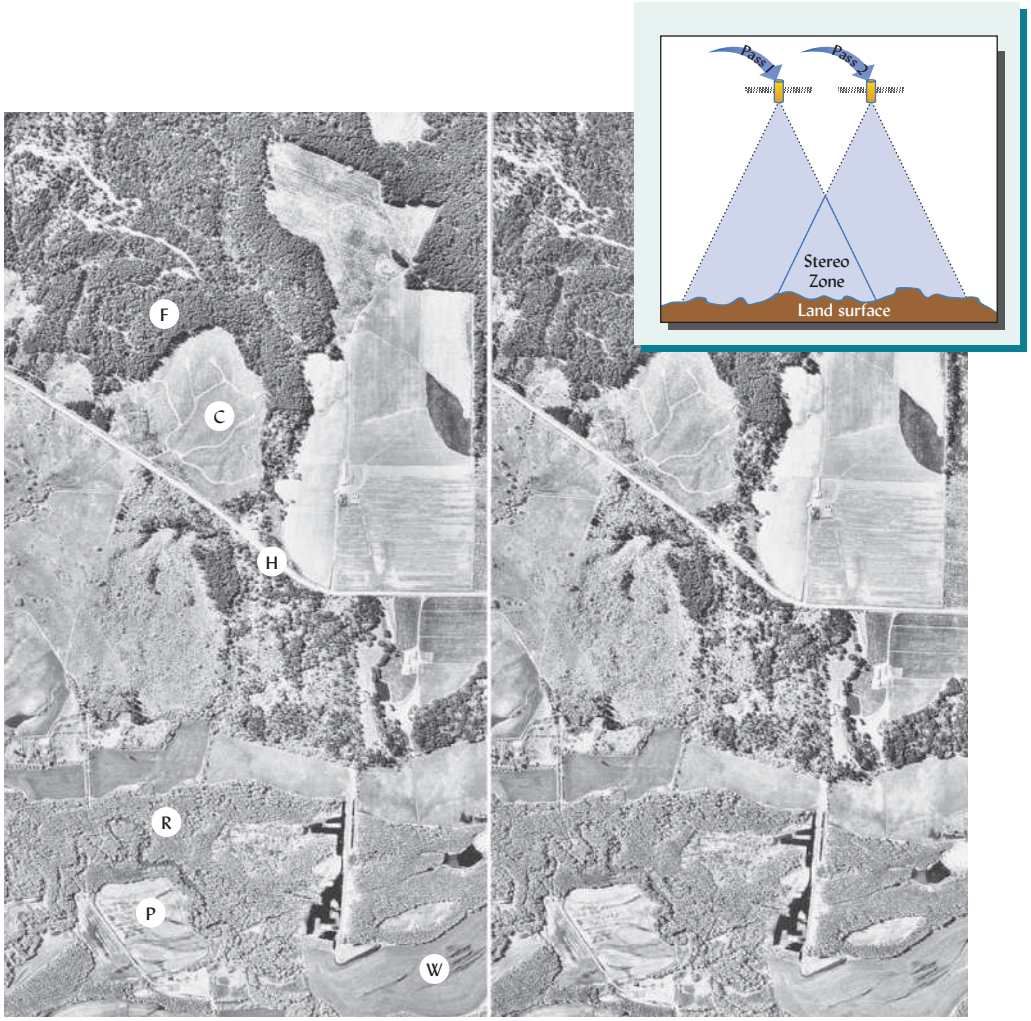

Figure 19.17 *A stereo pair of air photos provide overlapping coverage of the same ground area taken from a sensor platform (airplane or satellite) in two different positions. This scene in the Willamette valley of western Oregon, USA, includes soils that are mostly Humults and Xerolls. If you place a stereoscope over these photos (or just let your eyeballs relax until they superimpose the two images), your brain will be tricked into seeing the photos three dimensionally and the hilltops will seem to "jump off the page." Features include a coniferous forest* (F) *in the steeper terrain above the highway* (H)*, a roundish clear-cut area [medium-gray zone,* (C)*] with a network of logging roads (white lines with "nodes" indicating leveled areas where logs were loaded onto trucks). The lower third of the scene is the nearly level flood plain of a meandering river* (R) *with waterlogged spots* (W) *and other alluvial soil patterns* (P) *in the agricultural fields. The scale of these photos in the printed book is 1:10,000, so 1 cm on the photos represents 10,000 cm or 0.1 km on the ground.*

1 cm apart on a 1:20,000 air photo) gullies and streams indicate the presence of relatively impervious bedrock and clayey, low-permeability soils. Silty soils developed in loess usually produce a pinnate drainage pattern in which many small gullies and streams branch off from fairly straight larger streams at angles only slightly less than 90°. Streams with sharp, right-angle bends usually indicate that soils have formed from underlying beds of limestone.

In any case, image analysis can greatly speed field soil investigation by eliminating the need to investigate every mapping unit on the ground. However, the relationships between patterns on the photos and soil properties must be established afresh by field investigations (termed *ground truthing*) for each soil association or landscape type. The relationships determined are likely to hold true only for landscapes in a limited area, typically 500–1500 km^2.

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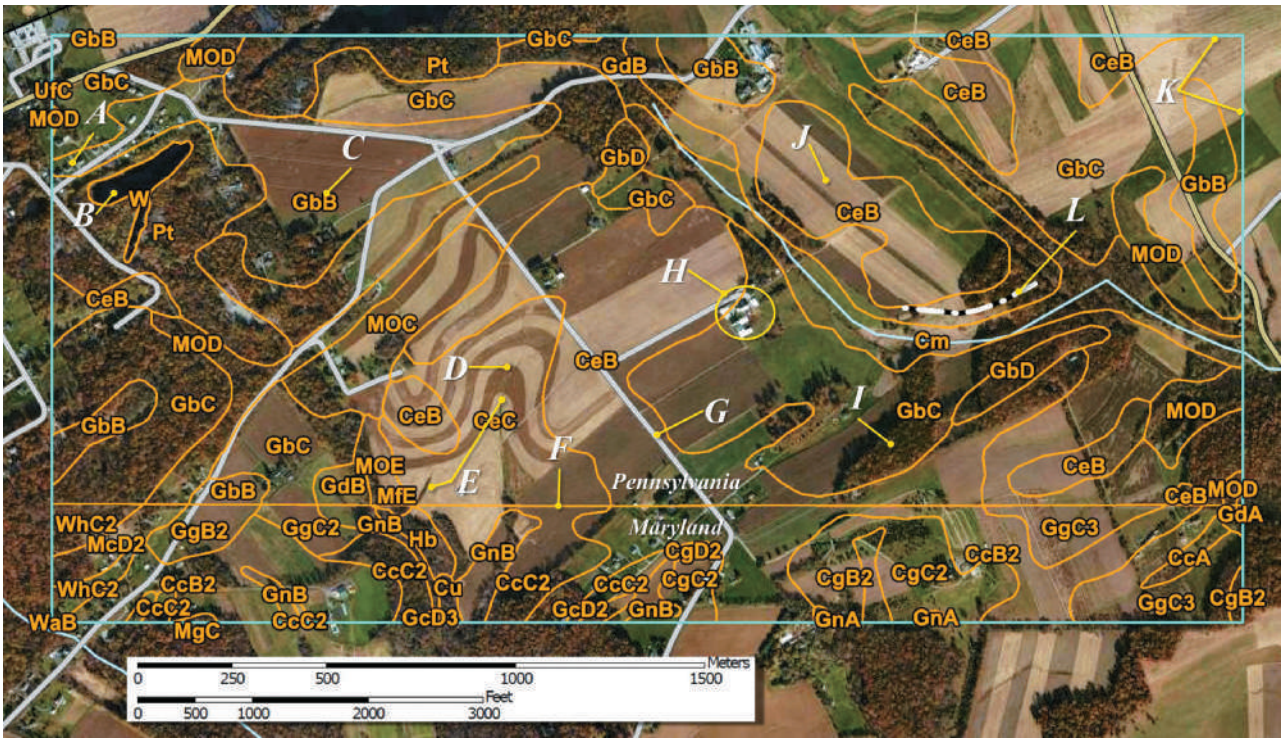

Figure 19.18 *A full color image of an area on the border between the states of Pennsylvania and Maryland, USA with soil boundaries and labels overlain. The white capital letters point to features of the landscape that could be helpful in mapping soils and interpreting the soil map for land use planning. A = houses; B = pond; C = soil mapping unit label; D = contour strip farming; E = two grasses waterways; F = state border; G = paved road; H = farmstead; I = coniferous forest; J = cropland with dry mature crops or brown residues; K = border of soil map; L = deciduous forest with symbol for intermittent stream. The scale is given in meters and feet. The map was made at a 1:12,000 scale but is printed in this book at 1:20,000 (1 cm on the map represents 20,000 cm or 200 m on the ground).* [Courtesy of Ray R. Weil using USDA/NRCS (2015a)]

Digital Elevation Models (DEMs)

The advantages just discussed of using a base map that provides detailed topographic information have been greatly increased with the advent of digital representations of the land surface relief termed DEMs. As the name suggests, a DEM is a mathematical model that interpolates between point measurements of elevation. In its most simple forms, the point elevation data may be created by on-the-ground land surveys or may be read from the contours of a topographic map. However, in modern practice, DEMs are derived from digital remote sensing sources, such as space-based radar (radio detection and ranging) surveys (e.g., Space Shuttle Radar Topography Mission, SRTM) or Lidar (Laser light detection and ranging) surveys flown by various types of aerial vehicles (airplanes, helicopters, UAVs). In any case, the creation of a DEM begins with a set of points for which precise horizontal (x, longitude and y, latitude) as well as vertical (z, elevation) locations are known. A spatial model then calculates surfaces that "connect all the dots" and a detailed relief picture emerges. The fact that x, y, and z coordinates are associated with every represented point—or pixel—on the modeled surface allows the calculation of relationship among points (e.g., "A is downslope from B"). Models can also calculate relationships between the topographic characteristics of any point (its elevation, aspect, slope) and information about that point derived from other geo-referenced datasets (soil type, clay content, temperature, etc.).

A very helpful option within DEMs is the ability to add "hill-shading" so that the surface appears to be lighted from one direction and the hills are bright on the side facing the light source and shaded on the other. This allows us to visualize the terrain relief as if we were looking down on the land surface in the late afternoon.

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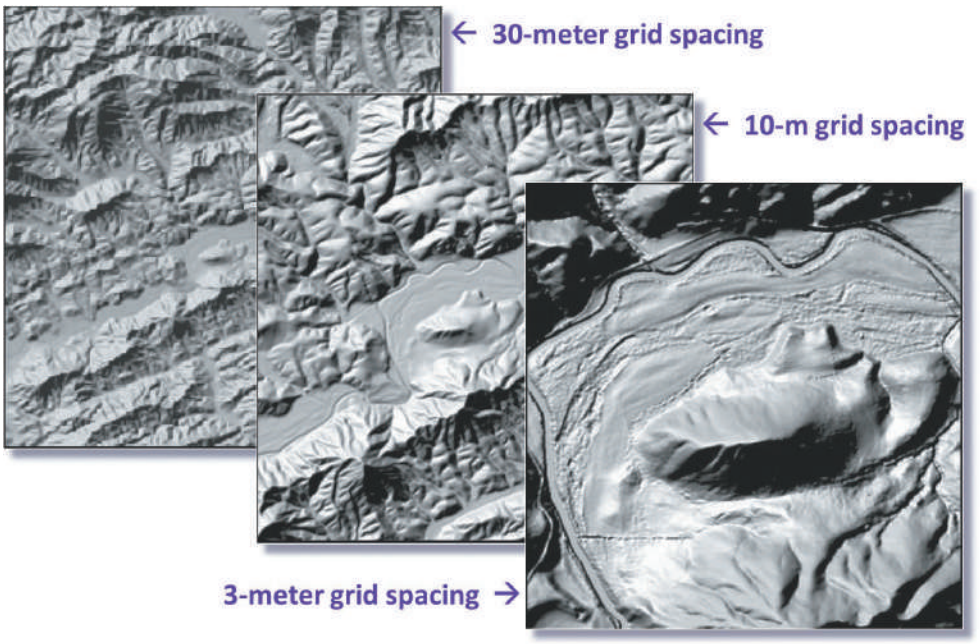

Figure 19.19 *Shaded relief images of an area in North Carolina derived from the three resolutions available in the U.S. national elevation dataset. Each image consists of a digital elevation model with hill-shading to better show the relief. Note how much more detailed relief in the flood plain surrounding the steep hill is represented in the 3-m DEM compared to the 30-m DEM. The 3-m grid DEM is said to be relatively high resolution while the 30-m grid DEM is relatively low resolution.* (Modified from Gesch et al. (2009))

When using digital imagery that may be presented on various computer screens rather than printed on paper, the concept of resolution may be more relevant than the concept of map scale. For a static map on paper, the scale indicates the density of information or how much detail can be seen. However, with a digital image, you can easily use software to "stretch" it on your screen, thus increasing the map scale, but without adding any greater information. As you stretch the image, it will simply become larger but more blurred or pixilated. The density of information and the amount of detail captured is represented by the image resolution, which tells us the smallest object that can be discerned or the area of land represented by each "dot" or pixel comprising the image. An example of image resolution for a DEM is given in Figure 19.19. The floodplain appears smooth in the 10 m image, but exhibits detailed relief (older stream channels, etc.) in the 3-m image. Note that stretching the 10-m resolution image so that the river flood plain and hill matched the size of these features in the 3-m image would *not* reveal any more detail of the relief.

Satellite Imagery

Many of the principles and techniques just mentioned with regard to air photos apply to satellite imagery as well. However, the imagery available from the sophisticated satellites now in orbit may be more complex and versatile than the types of air photos just discussed. Most satellite images are produced from computer-analyzed digital data obtained by multispectral scanners rather than by film cameras. The images are usually computer-enhanced by classification of each cell (pixel) of the image with regard to the type of vegetation, soil cover, land use, or similar theme. This classification is based on computer identification of each land cover's spectral fingerprint or pattern of reflectance over different wavelengths (as shown in Figure 19.15). An image may combine data sensed by different instruments, sometimes on different dates. In this manner, combinations of spectra can be used to identify vegetation types, soil properties, cultural features, water, and so forth.

The resolution of an image is said to be high if very small objects can be discerned. The resolution of satellite imagery available today is not as high as that obtained with low-altitude air photos, but it has steadily improved over the years. Images and multispectral data with resolutions as good as 2.5 m are available (usually for a substantial fee) from various satellites and sources. Internet software such as Google Earth® has made satellite imagery easily and freely available to the general public. The free software allows anyone with internet access to obtain a natural color image of virtually any location on the planet, although there is little choice of

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image resolution (varies about 80–2.5 m) date, with higher resolution generally available for the more urbanized areas and for areas of popular interest. For many areas, one can click on a clock icon in the lower left of the image to select images taken of the same scene but in various months of previous years—a very useful tool that may reveal variations in soils and vegetation not discernable on the most current image.

The capability of satellite imagery to clearly portray landforms and vegetation over a wide area is illustrated by Figure 19.20. Examine this image closely. It is a false-color Landsat 8 image of the Palo Verde valley where the Colorado River forms the border between California and Arizona in the United States. The image is a composite made from several different spectral bands. Rugged mountainous terrain and alluvial fans are visible surrounding a nearly level, irrigated valley. The arid landscape is virtually bare of vegetation, except in rectangular fields where irrigation water has been applied. The small circles in the lower left are center-pivot irrigation systems, which have moistened the soil, resulting in more absorption and less reflectance of light in dark circular fields about 0.5 km in diameter. Note the grid of streets that is the town of Palo Verde, near the center of the irrigation project. In bare fields different soils are visible as different blue-gray colors. Bright red areas are indicative of dense, green vegetation, mainly irrigated crops. Uneven areas of red to the east of the Colorado River indicate natural vegetation and weeds growing where gullies and drainageways have collected water from the river or the scant rains. Some of the farm fields have dry, bare

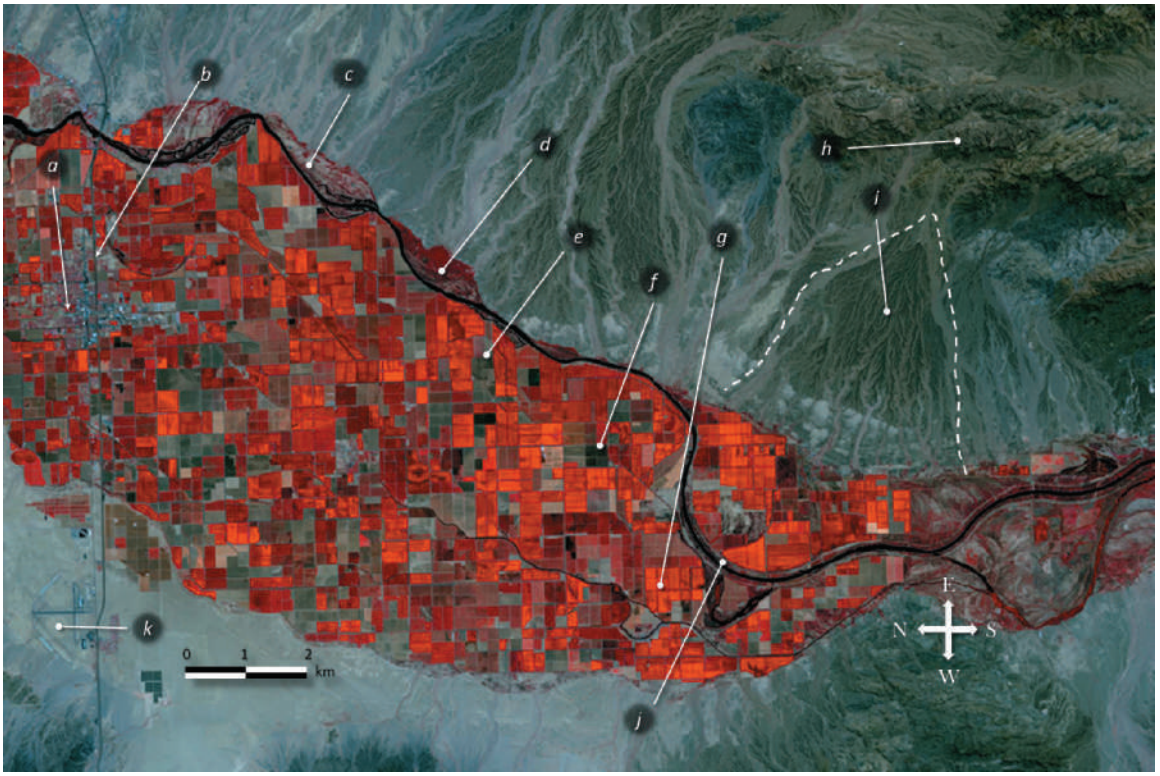

Figure 19.20 *An image of part of the irrigated Palo Verde valley on the border between California and Arizona in the United States (note directional indicator, north is to the left). It is a Landsat 8 OLI (Operational land imager) using TIRS (Thermal infrared sensor) image composite made from bands 2 (green), 3 (red), and 4 (near infrared). Lush green vegetation appears red, bare rock and dry soil appears blue-gray and water appears black. Note the features highlighted by the lettered pointers: a = park with irrigated grass in the town of Palo Verde; b = intersection of main roads in town; c = braided stream bed with sand bars; d = wild vegetation in moist soil along the river; e = a farm field with no vegetation and bare soil; f = four square farm fields flooded in preparation for planting; g = farm fields with green crop vegetation (red in image); h = rugged rocky cliff; i = alluvial fan outlined by dashed line; j = main channel of the Colorado River; k = small airport with perpendicular runways and faintly visible circle from formerly center-pivot irrigation. Some of the farm fields have dry bare soil because the City of Los Angeles purchased the water rights from the farmer.* (MDA Information Systems LLC)

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soil because the City of Los Angeles purchased the water rights from the farmer so that the city could obtain the water that would otherwise have been used for irrigating crops. Such satellite images can be used to verify that the owners of these fields are complying with water rights agreements.

Since 2013, Landsat 7 and Landsat 8 have been in polar orbits around the Earth providing coverage of any spot on the globe once every 8 days. The satellites can use as many as 11 wavelength bands, most with a resolution of 30 m. The U.S. National Aeronautics and Space Administration (NASA) makes these images and underlying data freely available on their website to anyone in the world. Global coverage at even higher resolutions (submeter in some cases) is available from the European SPOT 4 and 5 satellites, but generally at considerable purchase cost. Figure 19.21 provides an example of how the use of different wavelength band sensors on Landsat 8 can greatly influence what features can be discerned in an image. Detailed landforms, vegetation patterns, and soil variations made visible on such images can be a great aid in mapping soils.

Geo-scientists have developed countless applications for multispectral remote sensing. In Figure 19.16, we saw that different soil minerals reflect light energy in ways that can be sensed as unique spectra for each mineral. The application of this concept can be enhanced by computer algorithms that separate out and recognize each mineral spectra from a complex mixed spectral signal reflected by natural soils and rocks. Using a multispectral remotely sensed images and digital elevation models as a base map instead of paper maps or air photos provides data to plug into mathematical models that predict the spatial distribution of soil properties and help map classes of soils (Figure 19.22).

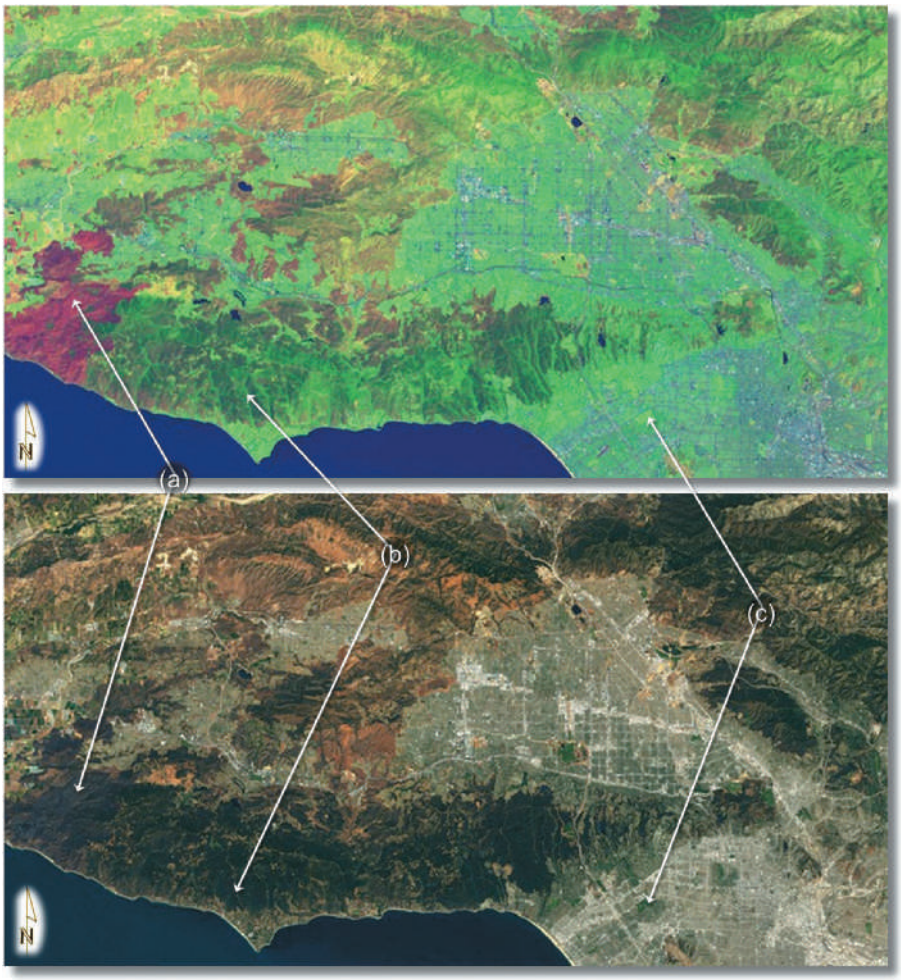

Figure 19.21 *Images of the California coast near Los Angeles, USA, made by Landsat 8 using different wavelength combinations.* (Lower) *Bands 2, 3, and 4 (visible blue, green, and red light) make the scene appear much as a human eye would perceive it. The city of Los Angeles appears mainly gray, most vegetation appears as a uniform dark olive green.* (Upper) *A false color image using bands 6 and 7 and showing shortwave infra-red (SWIR) as red, near infrared (NIR) as green, and deep blue as blue. These wavelengths distinguish differences in rock and soil types and soil wetness. A fire scare* (a) *that shows as red in the lower image is almost impossible to discern in the upper image. Lush vegetation on the alluvial soils in the canyon bottoms* (b) *shows up well as bright green lines in the lower image, but not in the true color image. Likewise, irrigated city parks* (c) *are much more discernable in the false color image.* (Images courtesy of NASA)

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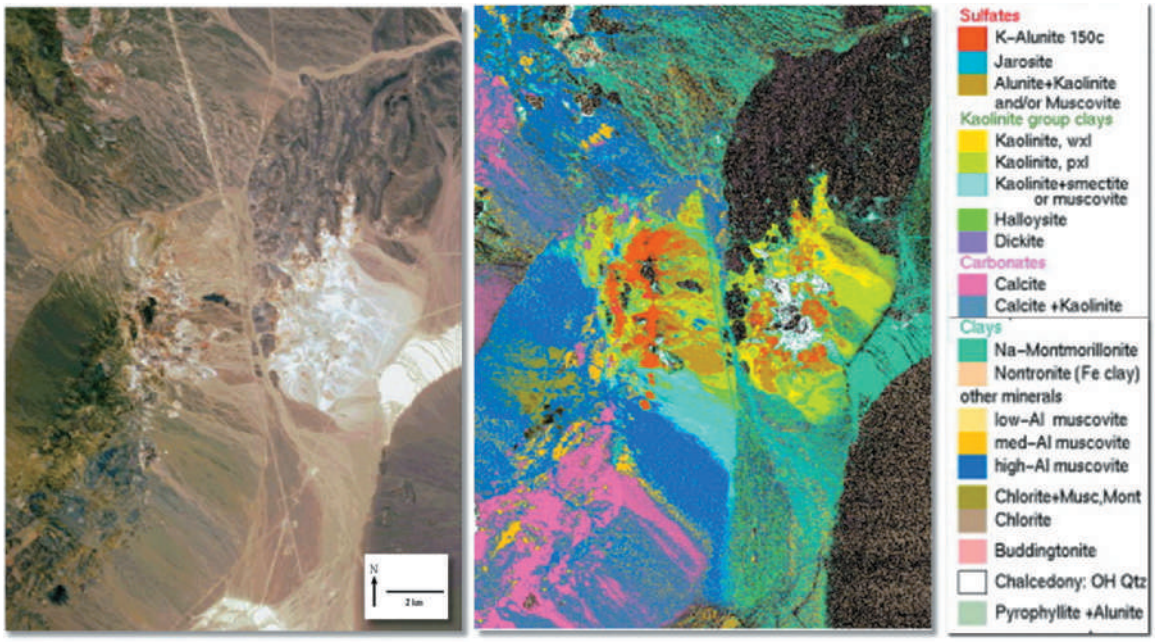

Figure 19.22 (Left) *Pseudo-true color composite AVIRIS image of Cuprite in Nevada, USA. The image used in this exercise was collected by the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) sensor. The image has a width of 10.5 km (614 pixels) and a length of 18 km (972 pixels). The spacing between pixels is 17 m, and the size of each pixel is about 20 m.* (Right) *A map of soil minerals showing the spatial distribution of such clay minerals as kaolinite, dickite, and montmorillonite, as well as small spots with jarosite, an iron-sulfate mineral indicative of acid sulfate weathering. The map was made using an advanced software program named Tetracorder (the inventors say the name was inspired by the "Tricorder®" remote analyzer seen in Star Trek). The program essentially identifies particular mineral materials by comparing many parts of the remotely sensed spectrum from a complex mix of materials (the unknown) to a large library of spectra from known materials. Refer to Figure 19.16 to see the characteristic spectra or reflectance "fingerprints" of three clay minerals.* [Modified from USGS images published in Clark et al. (2003)]

19.5 MAKING A SOIL SURVEY

All of the technologies discussed in previous sections can be used to help make a soil survey. A **soil survey** is more than simply a soil map. The glossary describes a *soil survey* as "a systematic examination, description, classification, and mapping of the soils in a given area." Under some circumstances, soil scientists make special-purpose soil surveys which do not attempt to delineate and describe natural soil bodies, but merely aim to map the geographic distribution of selected soil properties, such as suitability for an irrigation project or conformation to a legal definition of wetlands.

However, soil surveys have often been most valuable when they characterize and delineate natural soil bodies. Once the natural bodies are delineated and their properties are described, the soil survey can aid in making interpretations for all kinds of soil uses, not just those uses that were intended at the time the soil survey was conducted.

The basic steps in making a soil survey are:

1. *Mapping of the soils*. Described in Sections 19.1 to 19.3.
2. *Characterization of the mapping units*. See Section 19.2.
3. *Classification of the mapping units*. See Chapter 3 and Section 19.2.
4. *Correlation with other soil surveys*. Once a team of soil scientists completes a soil map, the map is reviewed by other soil scientists to verify that the soil boundaries match those mapped for adjacent areas and that the characterization and classification of mapping units are consistent with other soil surveys.

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5. *Interpretation of soil suitability for various land uses*. A report is written to accompany the soil map in order to describe the suitability of each mapping unit for various land uses. The interpretive tables in the report often reflect many person-years of experience and observation, as well as standard interpretations of measured soil properties.
6. *Organization* of all this soils information to make it available to users in the form of maps, tabular information, and electronic data files.

Soil surveys may be conducted at different *orders* or levels of detail, ranging from very detailed surveys that attempt to delineate virtually every soil body in the landscape (first order) to general reconnaissance surveys of very large regions or entire continents (fifth order). Different kinds of *mapping units* and remotely sensed data sources are used to produce different orders of soil surveys (Table 19.3).

Mapping Units

Soil Taxonomy (or some other classification system; see Chapter 3 and Appendix A) is usually the basis for preparing a soil survey. Because local features and requirements will dictate the nature of the soil maps and, in turn, the specific soil units that are mapped, the field *mapping units* may be somewhat different from the *classification units* found in *Soil Taxonomy*.

The mapping units may represent some further differentiation below the soil series level—namely, *phases* of soil series; or the soil mappers may choose to group together similar or associated soils into conglomerate mapping units. This choice is partially dictated by the scale of the map and therefore the smallest delineation which will be practical and legible. Very large scale maps (1:5000–1:12,000) may permit almost every discernable natural soil body to be mapped. The smaller the map scale, the more soil individuals on the landscape will have to be grouped together into various types of less uniform mapping units. This process is also influenced by the proclivities of the soil mappers—whether they are "splitters" or "lumpers." Carefully review the soil map displayed in Figure 19.18. Can you see that the intensity of mapping appears to have been greater on the Maryland side of the US border?

In USDA/NRCS soil surveys, there are several types of mapping units used to delineate soil differences. These are based on the concept of the map unit *component*. A map component is quite similar to a soil series, but the nature of the soil is more loosely defined so that several very similar soil series may be included in a single component—which would then be named for its most dominant series. Following are examples of soil mapping units as defined by their components.

Soil Phase. Although technically not included as a class in *Soil Taxonomy*, a *phase* is a subdivision based on some important deviation that influences the use of the soil, such as surface texture, degree of erosion, slope, stoniness, or soluble salt content. Thus, a Cecil sandy loam, 3–5% slope, and a Hagerstown silt loam, stony phase, are examples of phases of soil series.

Consociations. The smallest practical mapping unit for most detailed soil surveys is an area that contains primarily one soil component. Furthermore, that component is comprised mainly of only one phase of the named soil series. For example, a mapping unit may be labeled as the consociation "Saybrook silt loam, 2–5% slopes, moderately eroded." Quality-control standards for county soil surveys may indicate that a consociation mapping unit should be 50% "pure" and that the minor components present (formerly termed "impurities") should be so similar to the named component that the differences do not affect land management. That is to say, if you walk out on the land to areas mapped as the just-mentioned consociation and make 20 auger borings, on average, at most of the borings should reveal properties within the range defined for the Saybrook silt loam or a very similar soil series. However, it would be expected that a few of the borings would indicate a similar soil, such as the Catlina silt loam, in which the loess layer is somewhat thicker than for the Saybrook soil but for which land-use

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Table 19.3
DIFFERENT ORDERS OF SOIL SURVEYS
Soil surveys may be conducted at various scales or orders, ranging from very detailed surveys of small parcels of land to general surveys of very large regions. Different kinds of mapping units and remotely sensed data sources are used in producing different orders of soil surveys. The guidelines given in this table are only approximate.

	Order of Soil Survey				
	5th order	**4th order**	**3rd order**	**2nd order**	**1st order**
Type of survey	Reconnaissance	Reconnaissance	Semidetailed	Detailed	Intensive
Survey scale	1:250,000–1:10,000,000	1:50,000–1:300,000	1:20,000–1:65,000	1:12,000–1:32,000	1:1000–1:15,000
Size of mapping unit	2.5–500 km^2	15–250 ha	1.5–15 ha	0.5–4 ha	Smaller than 0.5 ha
Typical components of map units	Orders, suborders, and great groups	Great groups, subgroups, and families	Families, series, and phases of series	Soil series phases of series	Phases of soil series
Kind of map unit	Associations, some consociations, and undifferentiated groups	Associations, and some complexes, consociations	Associations or complexes; some consociations	Consociations and complexes; few associations	Mostly consociations; some complexes
Remote sensing sources	←	Landsat Thematic Mapper digitized data →			
	←				
		SPOT image digital data →			
		←	High-altitude aerial photography →		
			← Low-altitude aerial photography →		
Use of soil survey in land planning	← Resource inventory →				
		← Project location →			
			← Feasibility surveys →		
				← Management surveys →	

Adapted from USDA/NRCS (USDA/NRCS, 2015c).

interpretations are the same. Inclusions of *contrasting* soil components should occupy less than 15% of the consociation.

Soil Complexes. Sometimes *contrasting* soils occur adjacent to each other in a pattern so intricate that the delineation of each kind of soil on a soil map becomes difficult, if not impossible. In such cases, a soil *complex* is indicated on a soil map, and an explanation of the soils present in the complex is contained in the soil survey report. A complex often contains components named for two or three distinctly different soil series that present different management considerations. For example, a soil complex may contain some components that are well drained and some that are poorly drained.

Soil Associations and Broader Classes. As described in Section 19.1, relatively large-scale soil maps (e.g., third order) may display only soil *associations*—general groupings of soils that typically occur together in a landscape and could be mapped separately at a larger scale. Mapping units in fourth and fifth order surveys with scales smaller than 1:1,000,000 usually can show only broad classes of soils such as the dominant soil orders, suborder, and great groups present in delineated areas.

Undifferentiated Groups. These units consist of soils that are *not* consistently found together, but are grouped and mapped together because their suitabilities and management are very similar for common land uses.

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Figure 19.23 *A map of part of Los Angeles, USA, with soil delineations (blue lines) drawn on a base map consisting of a 3-m grid digital elevation model (DEM) with an ortho corrected air photo overlay. Note how well the DEM represents the relief of the hills in the upper edge and the downtown buildings* (d) *near the lower edge of the scene. The mapping was made at a scale of 1:24,000. Photo* (a) *provides an on-the-ground view of point* (b) *on the map, with downtown buildings in the far background. Photo* (c) *shows the profile of the Anthraltic Xerorthents soil at the location* (b). *Blue numerals code for soil map unit designations. Urban land refers to areas where 85% or more of the land is covered by impervious surfaces, such as buildings and pavement. Map Unit Key:1137 = Urban land-Vertic Haploxerolls-Anthraltic Xerorthents complex, 0–3% slopes; 1200 = Urban land, commercial, 0–5% slopes; 1201 = Urban land, commercial, 5–35% slopes; 1238 = Urban land-Montebello complex, 3–8% slopes; 1240 = Urban land-Anthraltic Xerorthents complex, 5–20% slopes; 1261 = Urban land, frequently flooded, 0–5% slopes.* [Photos courtesy of Ray R. Weil; map from Riddle (2015)]

19.6 USING SOIL SURVEYS

For more than a century, soil surveys have been conducted at various scales, using various classification systems and reported in various ways in different parts of the world (Box 19.2). In the United States, the effort to complete a detailed, standardized soil survey of the entire country has gone through several iterations and is still a work in progress. This effort, known as the *National Cooperative Soil Survey*, is an ongoing collaboration of federal, state, and local governments. The principal federal role is played by the U.S. Department of Agriculture Natural Resources Conservation Service (USDA/NRCS, formerly the Soil Conservation Service). For most of its history, the soil survey proceeded on the basis of local political jurisdictions (counties). While soils in most counties in the United States have been mapped, there are still some counties without any soil map. Other counties were mapped many decades ago and their soil surveys need to be updated. Paper soil survey reports are still available in libraries and many local conservation offices. Each soil survey report contains a general small-scale map showing soil associations for the entire country (or subcounty survey area) plus a collection of detailed soil maps drawn on black and white air photos at scales larger than 1:24,000 to show map units at the soil series or phase level (second order surveys, Table 9.4). Accompanying the collection of maps, each soil survey report also contains about 100 pages of *descriptive information* on the soil mapping units and their suitability for various land uses. In effect, the descriptive part of the report serves as a very elaborate key to explain the soil maps.

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BOX 19.2

TOWARD A GLOBAL SOIL INFORMATION SYSTEM

Lack of standardization among soil surveys has been a major impediment to the use of soils information in solving the world's pressing environmental and resource problems. The International Soil Reference and Information Centre (ISRIC), based at Wageningen University in the Netherlands, was established to promote integration among the world's soil survey efforts. It serves as a repository of so-called legacy data inherited from historical soil surveys around the world. Much of this old (as well as some new) soil survey information has been made accessible online as simple scans of the paper soil maps made during the twentieth century. More importantly, ISRIC is developing a standardized, user-friendly database of geo-referenced digital soils information. The Harmonized World Soil Database was constructed by standardizing the latest data from national and regional soil survey efforts along with soils information derived from the 1:5,000,000 scale Food and Agriculture Organization (FAO) Soil Map of the World (published in 1981 by the United Nations and updated several times since). This database includes >15,000 soil mapping units classified by both the World Resource Base and the US Soil Taxonomy systems (Appendix A).

One of the first user-friendly products of these efforts is SoilGrids1km (http://www.isric.org/content/soilgrids), a collection of updatable soil property and soil class maps of the world produced at a resolution of 1 km^2. SoilGrids maps are based on descriptions and data recorded by national soil survey teams from thousands of soil profiles during the past century (Figure 19.24). SoilGrids uses complex models to estimate soil property values or soil classes likely to be present at any given spot between the few locations where measurements were actually made. The project is intended to help link global and local soil mapping efforts. The FAO Soil Map of the World and associated soils data can be accessed using the SoilGrids viewer at http://soilgrids.org/index.html. One can currently zoom in on any location on the world soils map, but best resolution is 1 km^2 pixels. At this resolution the maps and soil information can be quite useful for feeding soils information into regional or global models that mathematically describe or predict ecosystem processes. These soils maps can be used as a layer in a Geographic Information System (GIS) (see Section 19.7) so that the influence of soil properties can be included in models predicting, for example, global climate change. However, such coarse resolution geo-information is not of much value in local land-use planning or farm management. Not only is the resolution too coarse for use in land planning, the reliability is rather low. Currently one can be less than 50% certain that any given pixel on the map actually has indicated the soil class or range of property values. The SoilGrids project is working to improve their global soil maps with an ultimate goal of a 100 m resolution (1 ha grid). Figure 19.25 is an example of a digital soil property map generated with SoilGrids1km.

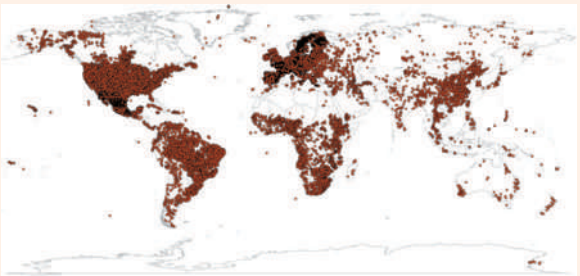

Figure 19.24 *Distribution of the soil profiles used in generating the SoilGrids1km world soil map.* (Courtesy of ISRIC)

The SoilGrids project is also coordinating with another separate but related international effort, The GlobalSoilMap.net project in which soil scientists from many countries are collaborating to make a new digital soil map of the world (see Section 19.8). They are developing sophisticated software for mapping soils and predicting soil properties at the fine resolution and high level of reliability needed for both ecological modeling and land management purposes. These efforts are currently hampered by scarcity and uneven distribution of soil profile data and by difficulties relating remotely sensed datasets to the factors that drive soil variations. However, the system is thoroughly automated so as improved models and data become available, they can be quickly incorporated.

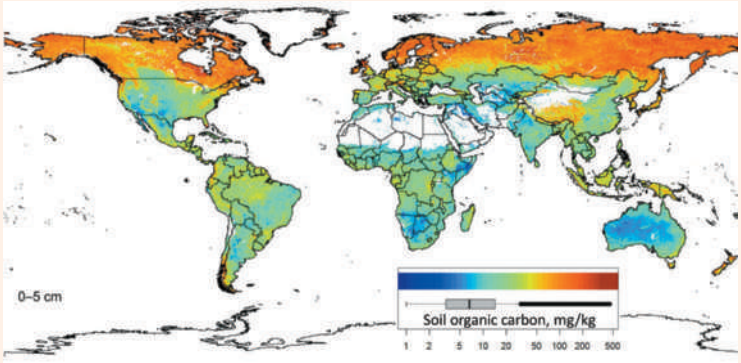

Figure 19.25 *Example of SoilGrids1km map layer showing soil organic carbon content in g/kg for the topsoil (0–5 cm). It is interesting to compare this map to that in Figure 12.24, which displays SOC per area of land surface to 1 m depth, rather than per kg of soil in the upper 5 cm.* [From: Hengl et al. (2014)]

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Since 2006, the U.S. National Cooperative Soil Survey has been reorganized to focus on 273 Major Land Resource Areas (MLRAs), zones defined by ecological characteristics, instead of the 3000+ politically defined counties formerly used to organize soil survey activities. Each MLRA is a geographically contiguous land area characterized by a common pattern of soils, land uses, water resources, and climate. For example, two MLRAs are the "Central Nebraska Loess Hills" and the "Alabama and Mississippi Blackland Prairies."

All U.S. soil survey information collected by the National Cooperative Soil Survey over the course of more than a century has now been integrated in the digital Soil Survey Geographic Database (SURRGO). Some of these data were entered directly into the system from recent field work, while much of the older data were transferred into digital form. This database has allowed the old static paper soil survey report to be replaced with a dynamic, computer-based online resource for soils information appropriate for many types of end-users. The SURRGO database is organized for easy electronic retrieval and integration with other digitized and geo-referenced information such as DEMs and remotely sensed databases on land use, vegetative cover, and the like. The systematic integration of soils and other databases will be discussed in Section 19.6.

Online Interactive Soil Survey

The online soils information system for the United States is known as Web Soil Survey (WSS). This interactive program is designed to provide soil maps useful in both land planning and modeling. Most areas of the United States are represented at either 1:12,000 or 1:24,000 mapping scales. At these scales, individual trees and houses are discernable on the air photo map base, and areas of soil as small as 1 ha can be delineated (Figure 19.26*a*). The mapping units are mostly consociations and complexes named for soil phases, although soil associations are also mapped. The maps are intended for natural resource planning and management by landowners, municipalities, and local jurisdiction governments. Some knowledge of soils data and map scale is necessary to avoid misunderstandings. For example, the mapping units are known to contain some variability and their boundaries are typically somewhat diffuse and cannot be precisely located. A map unit may specify the component soils, but not indicate *where* within the map unit area the various components are located. Therefore, these maps should *not* substitute for actual on-site investigation when a specific site is to be chosen for a construction project such as building a house or making a waste lagoon.

Web Soil Survey, like its paper predecessors, includes more than just the capacity to generate soil maps on air photo backgrounds. Each mapping unit has a wide range of soil properties and interpretations associated with it and this information can be queried and retrieved in tabular form, downloaded as datasets or displayed as interpretive maps.

How to Use Web Soil Survey

The WSS website is easy to use and provides various tutorials on its home page (http://websoilsurvey.sc.egov.usda.gov). Therefore we will provide only a brief overview here. There are four basic steps to producing a desired soil map and interpretative report.

Define an Area of Interest (AOI). The WSS initially displays the AOI tab and a map of the United States. The user can find the AOI by zooming in on the map display or by entering either a street address or geographic coordinates. Once an appropriate large-scale map is displayed, the boundaries of the specific AOI are *defined* on the map using one of two AOI tools to draw either a rectangle or irregular boundaries.

The AOI can be as small as 1 ha or as large as 40,000 ha. However, when zooming in on a very small (generally $<$10 ha) AOI, the website will warn that you have zoomed in beyond the scale at which the map was made and you should be aware that mapping is not as precise as it may appear. For a very large AOI (generally $>$10,000 ha), the soil map created may be too crowded with map units to be legible on the screen or when printed out. However, interpretive maps that combine many individual mapping units into a relatively small number of more general groupings can still be quite useful at this scale. The AOI used as an example in Figures 19.26 and 19.27 is 130 ha is size and is located just southeast of the hamlet of Singer, Maryland, USA.

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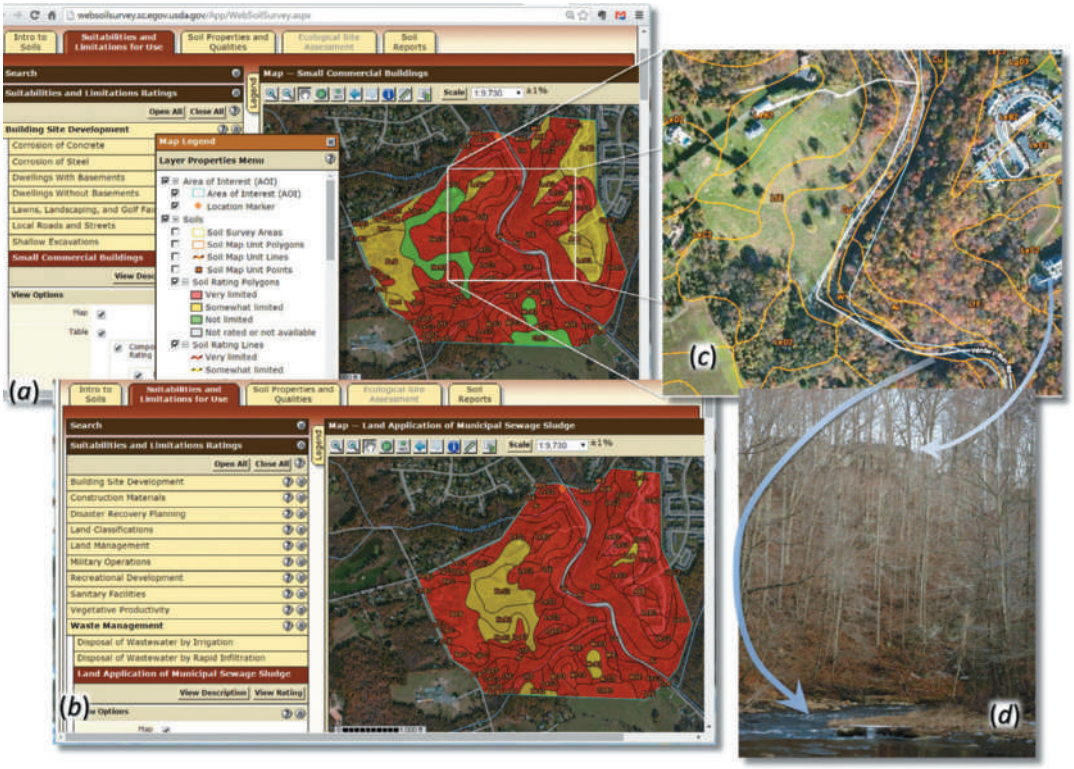

Figure 19.26 *Examples of interpretive soil maps generated with Web Soil Survey.* (a) *A map of soils with unlimited (green), somewhat limited (yellow), and very limited (red) suitability for siting of small commercial buildings.* (b) *A similar map showing soils somewhat and severely limited for application of municipal sewage sludge.* (c) *An enlarged section of the soil map showing an open pasture on the west side of Winters Run road and creek and forestland and a townhouse development on the east side of the creek.* (d) *A ground view of the creek with map unit Av, steep forested gorge (map unit LfE), and townhouses constructed on the ridgetop (map unit LeB2 which is only somewhat limited for small commercial buildings). Note the left side of each screenshot lists some of the many land uses for which soil limitation ratings are available.* [Images generated by Ray R. Weil using WebSoilSurvey (USDA/NRCS, 2015a)]

Create a Soil Map in the AOI. Once the AOI is outlined and enlarged for optimum viewing, the user clicks on the Soil Map tab to generate a detailed soil map of the AOI accompanied by a table listing each of the mapping units present, the map unit symbol, the soil name (usually a series or phase of a series), the land area covered by that soil, and its percent of the total area in AOI. The soil map displays soil boundaries and labels each delineated unit (as in Figure 19.18). The map unit labels may be a numeral (e.g., in Figure 19.23, map unit 1238 = Urban land-Montebello complex, 3–8% slopes) or an alphanumeric code (e.g., in Figure 19.27*a*, map unit CcB2 = Chester silt loam, 3–8% slope, moderately eroded). The map can be embellished by adding or removing features such as roads, rivers, town names, etc. The default map background is a natural color air photo, but a topographic map can be added to the background. Figure 19.27*b* is a screen shot of such a map created with Web Soil Survey.

Explore Soil Properties and Use Limitations. The Soil Data Explorer tab provides access data and interpretive information associated with the soils in the AOI. The topics for which information is available range from such soil properties as pH, cation exchange capacity, and saturated hydraulic conductivity on the Soil Properties tab to ratings on the Suitability and Limitations for Land Use tab for such land uses as constructing small commercial buildings (see Figure 19.26*a*), growing forest trees and crops; maneuvering military vehicles, or recycling sewage sludge (see Figure 19.26*b*), and dozens of other uses.

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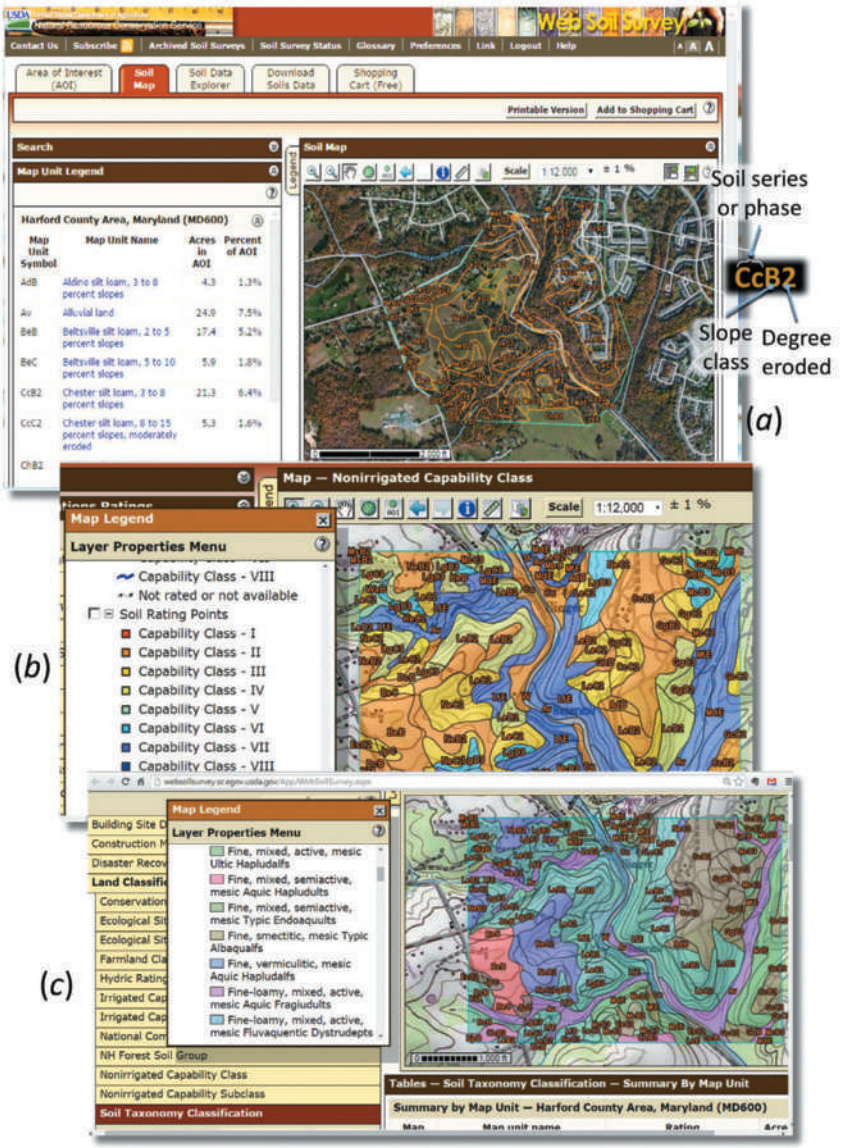

Figure 19.27 *Three maps generated with Web Soil Survey (WSS).* (a) *An area of interest (AOI) was delineated (blue-green boundary lines) on the ortho air photo base map. Then the Soil Map tab was selected to generate a detailed map of the soils in this AOI (which is the same 130 ha area near Singer in Maryland, USA, depicted in Figures 19.26, 19.28 and 19.30). The yellow lines are soil map unit boundaries and the gold colored letters are abbreviations for the map unit designations. In this case regional map unit abbreviations are used to indicate the soil name, slope, and the degree eroded (CcB2 in the labeled example). The map units, the main soil series within them, and their percent of the area of interest are listed in a table, part of which is shown at left.* (b) *A second map was generated using the Soil Data Explorer tab. Here the background features topographic contours and the map units are grouped together into Land Capability Classes II–VII. No areas here are classed as I or VIII (see Section 17.14).* (c) *In the third map, the soils have been grouped by Soil Taxonomy at the family level (see Section 3.3). For example, the bright pink areas are fine-loamy, mixed, active, mesic Aquic Fragiudults.* [Images generated by Ray R. Weil using WebSoilSurvey (USDA/NRCS, 2015a)]

The ratings given summarize qualitative observations of teams of soil scientists in the field, as well as numerical models, and take into consideration many different variables. As one example, consider the criteria used to rate soils for their limitations as sites for *small commercial buildings*, which the soil survey defines as one or two story structures without basements. The ratings are based on soil properties that affect the load-bearing capacity of the soil (and on properties that affect excavation and construction costs, including depth to water table, frequency of ponding or flooding, propensity for subsidence, shrink-swell potential (see Section 4.9), and compressibility (see Unified classification of soil, Table 4.11). The properties that affect the cost of excavation include flooding, depth to water table, ponding, slope, depth and hardness of bedrock or a cemented pan, and the amount and size of rock fragments.

Soil Explorer also allows classification of the map units according to their *Land Capability Class* (see Figure 19.27*b*), their *Soil Taxonomy family names* (see Figure 19.27*c*), or their *hydrologic group* (information in much demand for modeling urban storm runoff), among other classifications. The maps and tables of interest can be saved by adding a report to the "shopping cart" (so named even though the reports are free of charge). The user can also choose to

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download the data as files that can be integrated with nonsoils geographic information in complex spatial models.

"There's an App for That"

"SoilWeb" is a program developed jointly by University of California at Davis and USDA/NRCS. It makes data easily usable on mobile devices as well as on any computer. It is available as a smart phone application that uses GPS location information to show the type of soil in the location where the user is standing (Figure 19.28). SoilWeb uses Google® Inc.'s Google Earth® program to link to the U.S. national SURRGO database, and so can display soil maps similar to those created with Web Soil Survey, but with Google Earth® style and capabilities. SoilWeb can also display average soil profile data for map units in the SURRGO database such as the soil organic matter profile shown in Figure 19.28, *left*.

Example of Web Soil Survey Use

As an example of how the soil survey information is commonly used, consider the 130 ha parcel of land featured in Figures 19.26–19.28. Examining the soil map in Figure 19.26*c* we can determine that the parcel contains five mapping units encoded as Cu, LeB2, LeD2, LfE, and NeB2 (see also Figure 19.28, *right*). See Figure 19.27*a* for an explanation of this map unit coding system. These five mapping units are further described in Table 19.4, which also lists a few of the many interpretive ratings from SURRGO data as provided by tables in Web Soil Survey. If you were planning to develop a park on this site, the information in Table 19.4 would suggest that the Codorus silt loam (Cu) mapping unit would be suitable for a nature trail, but not for a visitor center with rest rooms. This scenario illustrates the type of use for

Figure 19.28 *"SoilWeb" is a program that makes the SURRGO soils data easily usable on any computer. It is also available as a smart phone application that uses the GPS location information to show the type of soil in the location where the user is standing. The on-the-ground photo* (right) *shows the view as seen by someone standing at the red spot on the SoilWeb map* (left). *The smart phone screen* (right) *shows profile diagrams for the Codorus and Hatboro soils. These alluvial Inceptisols account for 85% and 15%, respectively, of the Cu map unit on the flood plain of Winters Run where the user is standing. The upland map units in the background are dominated by the Legore soils and are distinguished mainly by the presence of the stony phase or slope steepness. The SoilWeb screen* (left) *can also display soil properties from the SURRGO database, such as the soil organic matter profile shown.* (Images courtesy of Ray R. Weil and USDA/NRCS)

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Table 19.4
EXAMPLES OF INTERPRETIVE INFORMATION PROVIDED BY A WEB SOIL SURVEY
The four mapping units described are among those in the site shown in Figures 19.26–19.28. The interpretations included are some of those that would be of interest for developing the site as a county park.

			Soil use limitation rating and reason			
Mapping unit code	**Name of mapping unit**	**Land use capability classification[a]**	**Camp areas**	**Septic filter fields**	**Paths and trails**	**Suitability for open land wildlife**
Cu	Codorus silt loam	IIw-7	Severe—flood hazard	Severe—high water table, flood hazard	Moderate—flood Hazard	Good
LeB2	Legore silt loam, 3–8% slopes, moderately eroded	IIe-10	Slight	Slight	Slight	Good
LeD2	Legore silt loam, 15–25% slopes, moderately eroded	IVe-10	Severe—slope	Severe—slope	Moderate—slope	Fair
LfE	Legore very stony silt loam, 25–45% slopes	VIIs-3	Severe—slope	Severe—slope	Severe—slope	Poor
NeB2	Neshaminy silt loam, 3–8% slopes, moderately eroded	IIe-4	Slight	Moderate—mod. permeability	Slight	Good

[a]See Section 17.14 for an explanation of the USDA Land Capability Classification System.
Data courtesy USDA/NRSC Web Soil Survey.

which the SURRGO data and maps are best suited—planning how to best use different areas in a particular parcel of land or choosing the best suited among several parcels of land available for a particular project.

Suppose you were a local planner tasked with developing a new park. You might use Web Soil Survey maps to help select the most suitable site from among those potentially available. Your soils selection criteria might include: (1) good soils on which to make for trails and picnic areas, (2) soils with few limitations for building a visitor center, (3) soils that can accommodate a septic drain field for the public restrooms, and (4) land with good potential for woodland productivity. However, using a series of maps, each displaying only one criterion, you would find it difficult to determine a site that is the best match for all four criteria. To do this, you would like a system for integrating the spatial information from all the individual criteria maps into a single map that displays the overall ratings for developing a park. In other words, you would like a GIS, a tool to which we will now turn our attention.

19.7 GEOGRAPHIC INFORMATION SYSTEMS (GIS)[6]

For complex land planning analyses, or for understanding ecosystem processes, the enormous quantity and diverse types of information stored in digital databases can be used to best advantage with the help of computerized GIS.

[6]For a comprehensive introduction to GIS, see Halls et al. (2007).

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An information system is a series of organized steps used to handle information or data, including the plan for the collection of data, actual collection of the data, manipulation of the data, and, finally, use of the data in making a product, such as a report, model, or map. A GIS includes the following five steps: (1) data acquisition, (2) preprocessing, (3) data management, (4) manipulation and analysis of data, and (5) product generation.

The soil mapping process described in Section 19.3 could be part of the data acquisition step, as could the collection of remote sensing data from satellites, information from old soil maps, reports, and assemblage of social or political data such as zoning ordinances. The data must be preprocessed to create a data layer that can be integrated with other data layers. The layers can be integrated in the GIS because every point is georeferenced to its exact location on the Earth's surface.

Data for any variable can be geo-referenced either as **raster data** or as **vector data** (Figure 19.29). A raster data layer divides the land area into a uniform grid of square cells or rasters. The size of the cells, which determines the resolution of the data, is typically between 3 m and 1 km on a side. In a raster data layer for any variable (soil clay content, soil conductivity, etc.), every geo-referenced cell in the grid is associated with a value. Remote sensing data are typically captured in raster form.

In contrast, vector data consists of areas, called polygons, delineated by boundary lines. The area within a polygon is treated as uniform and is assigned a particular value or range of values that defines a class. A class represented by a polygon could be a named soil series or a range of values for a quantitative variable (e.g., 15–25% clay). Traditional soil mapping creates vector data by delineating polygons on a map and assigning each with a soil name and set of associated properties. A GIS can process both types of data and even interconvert between them.

Once all the necessary information has been downloaded or entered into the database, it can be managed with computer programs and manipulated to create new types of information and insights. Finally, a product such as a map or report is produced. A number of complex computer programs have been designed to carry out the last three steps in a coordinated manner. Figure 19.30 shows an example of a relatively simple GIS product. The map in this figure is based on data imported from SURRGO into a GIS. The map has simplified a set of more than 90 different mapping units by grouping them into three simple, spatially displayed categories. Such single attribute maps are easy to generate using Web Soil Survey.

The just-mentioned map (Figure 19.30, *top*) comprises a single *layer* of information. Web Soil Survey can display only one such layer of soils information at a time (along with topographic and air photo imagery layers). A GIS can be used to integrate many such layers of soils and other information to produce new spatial attributes and highlight spatial relationship that would otherwise not be obvious.

As a hypothetical example of the use of a GIS, consider the following scenario. A local agency wishes to find a suitable 50–100 ha site for a public park in one of 20 tracts of land available for purchase and delineated in the general area where the park is desired (Figure 19.30). The

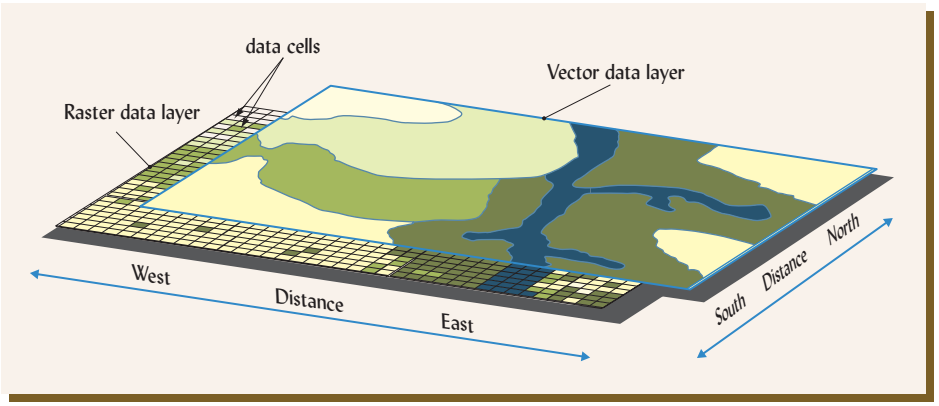

Figure 19.29 *Two types of spatial data, raster and vector, for the same variable. In a raster data layer the land area is represented as a uniform grid of square cells called rasters. Vector data consist of areas, called polygons, delineated with boundary lines. A GIS can process both types of data and even interconvert between them.* (Diagram courtesy of Ray R. Weil)

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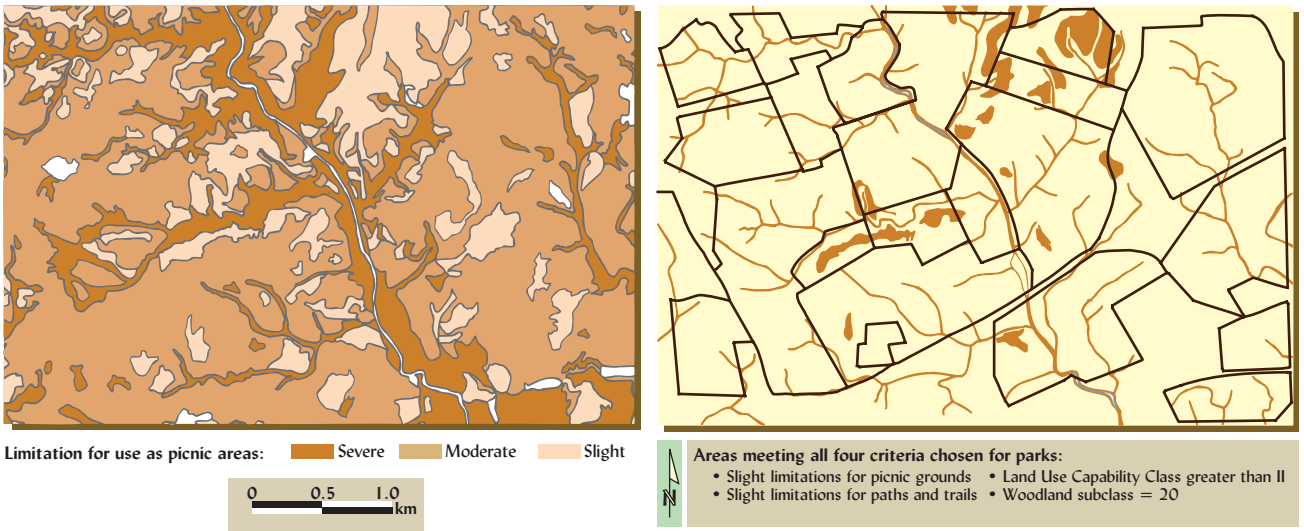

Figure 19.30 *Use of a GIS to overlay several layers of vector data about soils.* (left) *A simple interpretive soil map covering about 2400 ha in Harford County in Maryland, USA. Each of the thousands of soil polygons in the map has been rated as to limitations for use as picnic areas. The dark brown polygons along the major streams are either too steep or too wet to be favorable for picnicking and, therefore, are in the severe limitations category. This map is a single layer in that it contains only information on use for picnic areas (nonsoil areas are left blank).* (right) *The same area, with shaded polygons determined to be suitable sites for a new park according to the four criteria listed. The land use capability class restriction (LUCC > 2) avoids taking prime farmland out of production. The property of "park suitability" is a new attribute created by the geographic information system. In addition to "park suitability," two other layers are displayed: (1) streams (light, branched lines) and (2) boundaries of 20 hypothetical tracts of land (heavy, straighter lines). Which tract of land should the local government purchase for a new park?*

planners decided that the site for the park must meet the four criteria listed under Figure 19.30, *right*.

Each polygon is associated with the appropriate interpretive and descriptive data as downloaded from SURRGO or Web Soil Survey. The GIS computer program searches for mapping unit polygons that meet all four of the criteria and creates a map with dark brown shading used *only* for the qualifying polygons. Finally, the boundaries of the 20 tracts of land, as well as the locations of streams, are plotted on the map. The resulting map is shown in Figure 19.30, *right*. The uppermost tract just right of center appears to contain the largest area of land meeting the all criteria for the proposed park.

In many land planning projects, soil properties comprise just one of several types of geographic information that must be integrated in order to take best advantage of a given site or to find the site best suited for the proposed land use. Planning the best use of different farm fields, finding a site suitable for a sanitary landfill, and designing a wildlife refuge are some examples of projects that could make good use of both soils and nonsoils geographic information. Nonsoils information to be considered might include topography, streams, vegetation, distance from public roads, and present land use. A GIS can be used to combine all these types of information, giving greatest weight to those factors that the planner deems most critical.

An example of such an integrated GIS model is shown in Figure 19.31. Here, the objective was to develop a plan for conserving a rare and endangered wildflower, northern blazing star. The nature of the land, including soil properties such as drainage and water-holding capacity, as well as existing vegetation and legal conservation easements, determines which areas should be given priority in the effort to protect the wildflower habitat. A number of maps showing the spatial distribution of such soils and nonsoils factors were overlaid or combined in order to produce a final map that differentiated zones on the island according to their priority in a conservation action plan.

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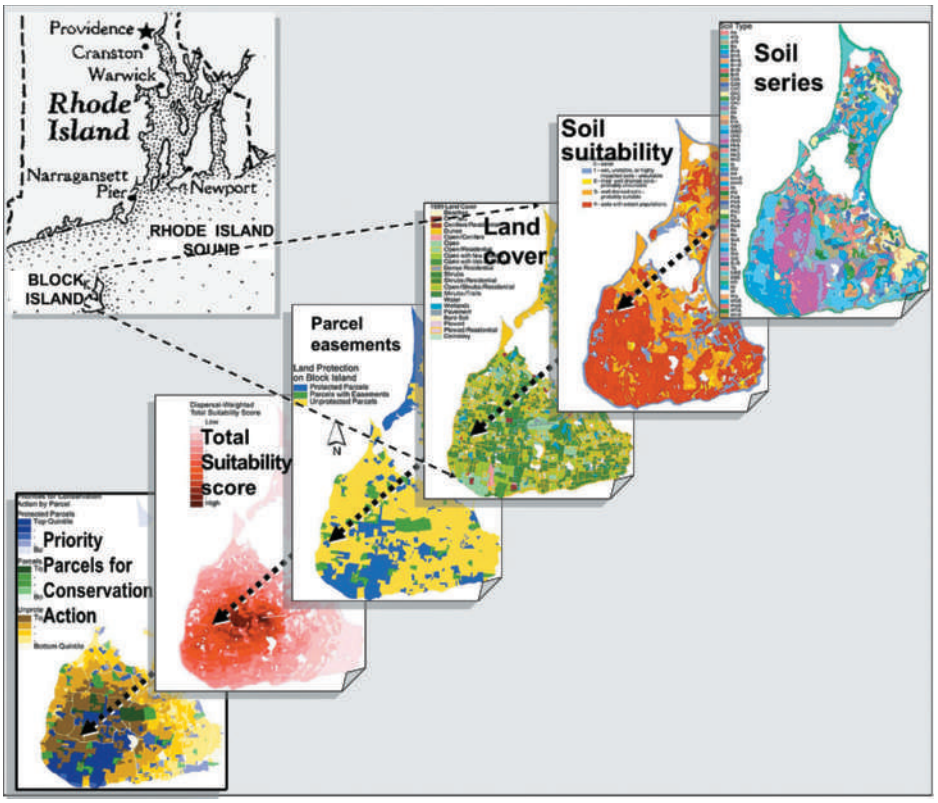

Figure 19.31 *Using a geographic information system (GIS) to integrate spatial information on soils with physical, biological, and social land attributes to identify new land categories for a particular purpose. In this example, the goal was to save the rare wildflower, northern blazing star* (Liatris scariosa var. novae-angliae). *The plan prioritizes habitat patches for conservation action, based on habitat suitability and the spatial relationship of each patch to the entire population of the flower on Block Island, RI. The soil series (first map layer) were grouped by suitability for northern blazing star habitat (second map layer) and used as a criterion along with existing land cover (forest, shrubs, wetlands, etc.) and existing conservation easements to prioritize land areas for the conservation effort. The final product (leftmost map) shows which parcels of land should be given high, medium, or low priority in the conservation program.* [Modified from maps courtesy of Vadeboncoeur (2003)]

Application of GIS technology can provide rapid data access, multidimensional analysis, and compelling graphical output, all of which can promote more effective resource management decisions. A major advantage of GIS is that it can be used for "what if" scenarios in which the investigator can change any combination of attributes and the GIS will predict how the end product would change as a result. As more soils information becomes available in digital form, its use in making land planning decisions based on GIS analyses will undoubtedly become increasingly common. The quality of those decisions will continue to depend on the quality of the geographic soils information provided by soil scientists and the quality of the decision criteria developed by planners and their clients. Likewise, the quality of predictions from spatial models will depend on both the quality of the data input, the effectiveness of the computational models employed, and the insights of the scientists applying the GIS.

19.8 DIGITAL SOIL MAPS: PROPERTIES OR POLYGONS?[7]

Digital soil mapping differs fundamentally from the traditional type of soil mapping that is the focus of Sections 19.4–19.6. The difference lies not so much in the computerization, but in *what* is being mapped. Traditional soil maps delineate soil bodies or individuals which are represented as distinct polygons (bounded areas) on a map. Each polygon represents a named class of soil, and that name carries with it a "picture" of a certain type of soil, its typical soil profile and all of its properties. Digital soil mapping, on the other hand, usually aims to represent

[7]For a brief story about how the world's soil scientists began collaborating on a global digital soil map, see Fisher (2012); for a comprehensive treatment of the global digital soil mapping effort see Arrouays et al. (2014) and for a somewhat technical discussion of "data fusion" see (Grunwald et al., 2015).

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quantitative spatial variation of soil *properties* or *attributes*, not qualitative distribution of *soil bodies.* The quantitative gradations across the map are the result of statistical models that estimate the values for a given attribute at all the points between the places where actual measures were made. While the math of modeling and spatial statistics is beyond the scope of this book, we will consider some of the underlying concepts.

Math, Models, and Maps

It was the increasing demand by scientists for a soils data layer in their GIS models of Earth processes that was the principal impetus for the development of digital soil mapping and the global collaboration to advance it. Mathematical models are used to understand spatial distributions and temporal changes in various ecological processes. For example, a model may attempt to predict how greenhouse gas emissions might change as land is converted from forest cover to cropland; or how storm water runoff flows may change as a watershed becomes more urbanized. Scientists and planners may focus their models on the watershed of a small stream; or they may address ecosystems across regions, continents, and even the whole Earth. Clearly, such users and their ecosystem models are in need of raster data about soil properties, with values associated with every point on the land surface. This is quite a different type of soils information than provided by the traditional vector-data soil maps. The vector polygon soil maps still can serve quite well for a farmer trying to decide which of his fields is best suited to a particular crop, or a developer looking for the best places to build her next housing project.

Figure 19.32 provides an example of how a map can display the continuous spatial distribution of a soil property as a raster data layer when only relatively few discrete

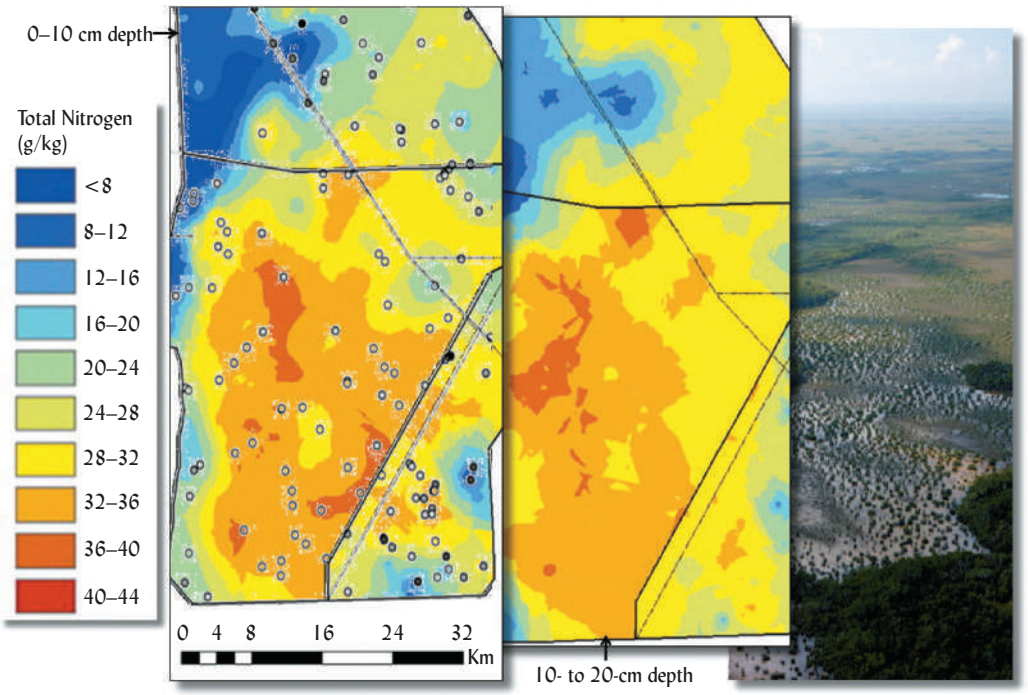

Figure 19.32 *The spatial distribution of nitrogen at two depths in the Histosol soils of a 233,000 ha water conservation district in the subtropical Everglades wetland system in Florida, USA. Total N was actually measured in soil cores taken at 388 random locations (approximately one per 600 ha) represented by small circles on the map. The N concentration in these ranged from <8 to 44 g/kg. The maps were drawn by a computerized geostatistical model that used the 388 actual measurements to estimate thousands of likely N concentrations in all the map cells not directly measured. This process of estimating values between measured points is called interpolation. Note in most areas where N is high in the upper 10 cm, the soils are also high in N in the 10- to 20-cm layer. Ecologists can use such maps to compare the spatial patterns of soil N to the distribution of plant productivity, organic matter decomposition rates, and other processes known to drive ecosystem functions. This information allows a better understanding of how the ecosystem is changing and how it might be restored.* [Modified from Bruland et al. (2006)]

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on-the-ground measurements are actually made. The N concentration at each point on the land surface (i.e., in each raster cell) is estimated by a mathematical model that takes into consideration the N values at all nearby locations where the soil was actually sampled and analyzed, generally giving greater weight to the values from the nearest locations. The color changes on this map do *not* represent boundaries between polygons (i.e., soil bodies or individuals) as this is not vector data. Rather, the steps of colors merely help us visualize the continuous quantitative variation of modeled soil N concentrations across a landscape. If a different set of arbitrary class ranges of N concentration had been chosen for color coding (say, 0–10, 10–20, 20–30 . . . instead of 0–8, 8–12, 12–16 . . . mg N/kg soil) the map and all its "boundaries" would look quite different, but the spatial trends and the models underlying the map would be the same. In fact, the authors of this map could have chosen to display the same information using continuous shading from light to dark with no "boundaries" at all. The real value of such maps is not the pretty "picture," but the underlying quantitative geo-referenced data which can be integrated along with other data layers into complex quantitative models. One of the properties of such a map that make it especially valuable is that the statistical models that estimate the attribute values (such as N levels in this map) can also calculate the *uncertainty* of these estimates, allowing the users to know how confident to be in the trends shown in different maps—or in different portions of a single map. This capability associated with digital soil maps is analogous to the probabilities used in weather predictions. Thus, for a certain location on the map in Figure 19.32, a decision maker using the map could determine that "there is a 90% chance that soil N concentration is between 8 and 16 g/kg."

Digital Maps for Quantitative and Qualitative Attributes

Figure 19.33 includes two digital soil maps using raster data (the Harmonized World Soil Database), but for two different kinds of variables, namely, a continuous quantitative variable

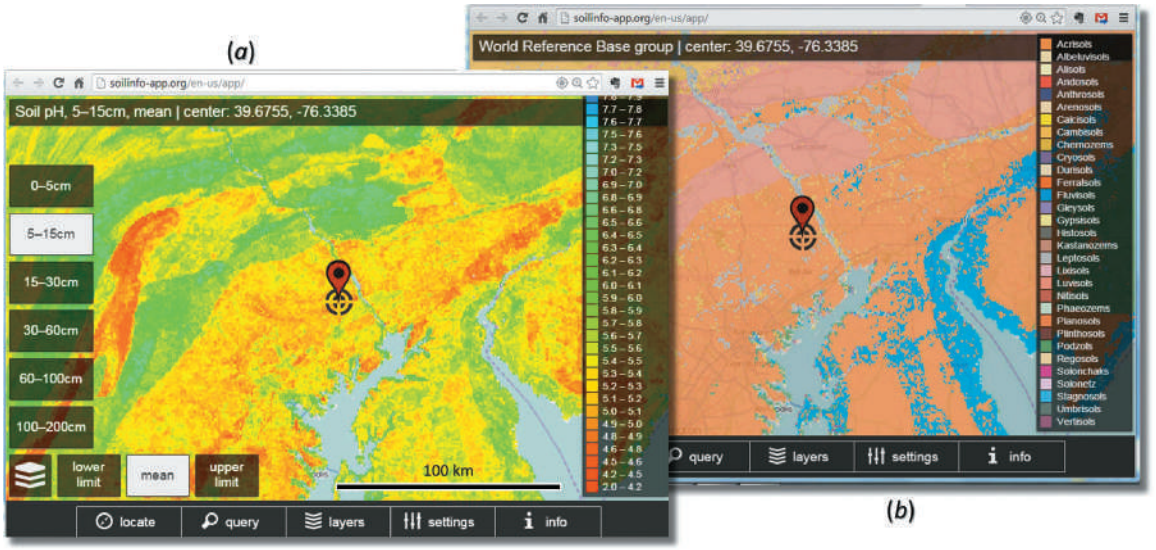

Figure 19.33 *Two soil maps created with the easily accessible Soil Info program using the Harmonized World Soil Database (HWD) and digital mapping techniques. As discussed in Box 19.2, this HWD is a raster database (with 1 km^2 grid cells) in which the attributes (data values) of each cell are estimated by models that use both the values for this attribute actually measured at a set of locations and a number of other attributes measured by satellite sensors (spectroscopy and LIDAR, etc.) for each cell location.* (a) *The soil pH estimated for a particular cell (a pixel in the map image) is based on nearby measured pH values, but also on the quantitative relationship ascertained for how soil pH varies across a landform on a DEM and with changes in vegetation greenness sensed by spectroscopy. In the case of soil properties like pH (shown), carbon content, or bulk density, estimates are made for each of several depth increments in the soil profile (see menu key on extreme left).* (b) *The map on the right displays soil classes rather than a quantitative soil property. Still, the discrete class associated with each pixel (1 km^2) on the map is determined by a complex model.* [Maps made by the author using SoilInfo website (ISRIC, 2015)]

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(left hand map) and a discrete class variable (right hand map). The soil pH, a continuous quantitative variable, was estimated for each particular cell or pixel in the map based partly on the nearest measured pH values (as was the case for N in Figure 19.32). However, the estimates were also based on the quantitative relationships ascertained for how soil pH varies with such *covariate attributes* as relief (as described by a DEM) and with changes in vegetation greenness (as sensed by satellite spectroscopy), etc. This blending of remotely sensed continuous data with data measured proximally (on the ground) at selected locations has been referred to as *data fusion*.

The map on the right in Figure 19.33 displays soil classes rather than a quantitative soil property. Still, the World Reference Base soil group name (Acrisols, Luvisols, etc.) associated with each pixel (1 km^2) on the map is determined by a complex model. Where only a general soil map (e.g., map scales coarser than 1:1,000,000) with very large polygons was available, the model used various remotely sensed raster data layers to estimate spatial variation of 1 km^2 cells *within* each large polygon originally mapped. In other places, where the fine scale soil maps were originally made with very small polygons (0.001–0.01 km^2), the models aggregated many small polygons together into each 1 km^2 cell, naming the cell after the soil class most dominant among the small component polygons.

Digital Soil Mapping from the Ground Up

The main conceptual steps in making a digital map are outlined in Figure 19.34. As just suggested, quantitative models that make raster estimates of soil properties are much more powerful if they not only interpolate between soil measurements, but also integrate relationships

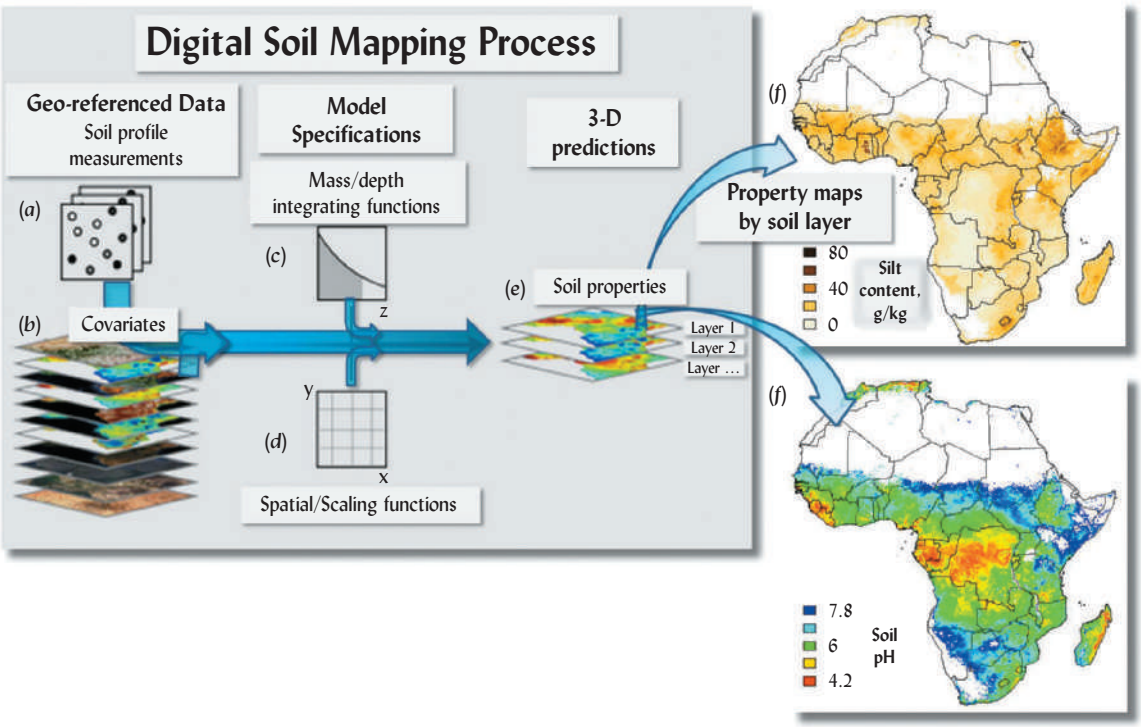

Figure 19.34 *Digital soil maps represent the spatial variation in quantitative soil properties. The quantitative gradations across the map for a given soil property (e.g., silt content) result from statistical models. These models estimate the values for the space between the places where actual measurements were made. Measurements made on various soil profile layers* (a) *at a finite number of sample points are integrated by these models* (c,d) *with values for other landscape properties (e.g., slope, vegetative cover, rainfall) obtained from remote sensing or other geo-spatial models* (b). *In this way, maps showing variability in a soil property for a particular soil layer are made* (g,f). *At any specific location, these maps indicate both the value of the property (e.g., 22 mg silt/kg soil) and an estimate of uncertainty (e.g., 90% certainty that silt content is between 15 and 29 mg silt/kg).* [Modified diagram and maps courtesy of African Soil Information System (AfSIS) (2015)]

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with other geo-referenced attributes, such as temperature, rainfall, vegetative cover, land use, topography, etc.

A deep understanding of the concepts of soil formation (as discussed in Chapter 2) is essential for successful digital soil mapping. One reason for this is that the remotely sensed covariate variables that help models predict spatial variation in soil properties are usually related to Hans Jenny's classical five factors of soil formation (see Section 2.2) expressed in Equation (2.10) [$S_i = f(cl,o,r,p,t)$]. At the continental scale, the factors related to climate (cl), parent material (p), and time (t) most frequently wield a decisive influence on soil properties. At more local scales, the decisive factors are mainly those related to topography or relief (r) and organisms (o, mainly vegetation types and human activities). These relationships to soil formation processes explain why spectral indices of vegetation types (o) and LIDAR data on relief (r) are so valuable in fine scale digital soil mapping.

In-depth knowledge about soils is also needed to be sure the various datasets and models are used in the proper context. As an example, consider landscapes (*a*) and (*b*) shown in Figure 17.50. These eroded hilly landscapes in different climatic zones exemplify why prediction models must be tailored for specific soil environments if they are to estimate how a soil variable (soil pH, in this case) changes across a landscape. The model should predict higher soil pH on the hilltops and lower pH in the valleys of the semiarid landscape where calcareous subsoil materials are exposed, but the opposite trend is likely in the humid landscape where the subsoil materials exposed on hilltops are acid clays. Thus the accuracy of the final maps is only as good as the quality of input data and the appropriateness of the interpolation models used. Currently, most models are able to predict only 20–50% of the spatial variability in a soil attribute, so the uncertainty associated with mapped values can be quite high. The predictive power of the models and the accuracy of digital soil maps will undoubtedly increase as more and better soil data are combined with more effective covariate models.

One approach to achieving improved data quality and model effectiveness is that being taken by African Soil Information System (AfSIS). Their goal is to produce digital soil maps (not maps of soils) for most of the African continent. They set about to obtain soil data according to a specialized random sampling plan that represents the range of soils and landscapes with a limited number of actual measurement sites while maximizing the ability for statistical interpolation between sampled points. Their field sampling methodology called the Land Degradation Surveillance Framework (LDSF) involves sampling 60 sentinel sites (each a 100 km^2 square) randomly located across sub-Saharan Africa. Nested within each sentinel site are 16 randomly located sampling clusters 6 km^2 in size, and within each cluster are ten 1000 m^2 sampling plots, and inside each of these sampling plots are four 100 m^2 subplots.

Strict randomization at each level is key to ensure the most statistical power and avoid biases. To achieve this randomization, the location of each cluster, plot, and subplot is determined by a computer program and located on the ground by scientists using GPS who sample in the exact spot the randomization dictated (unless that happens to be in the middle of a lake or the side of a cliff!).

This type of sampling scheme is much more powerful and in great contrast to the usual coarse survey of vast area that tends to collect samples at convenient stops along existing roads. Figure 19.35 illustrates the application of this nested sampling scheme to generate a map of organic carbon concentrations to the soils of a forest sanctuary preserve in Kenya. The measured soil data from the nested sampling scheme with two sentinel sites was interpolated with models using LIDAR relief and fine resolution (2 m) satellite imagery of reflectance spectra (see Section 19.3) that indicated woody vegetation cover and other variables.

Low soil carbon was observed along sandy river banks, and high soil C was found on hills with relatively dense tree cover. The soil carbon map was designed to assist in plans for sustainable land management interventions when considered along with maps showing other variables such as soil fertility, slope steepness, and vegetative cover. For example, low carbon soil areas with few other constraints might be targeted as places where cattle herders should corral their livestock to enrich the soil with manure to increase soil carbon and vegetative productivity.

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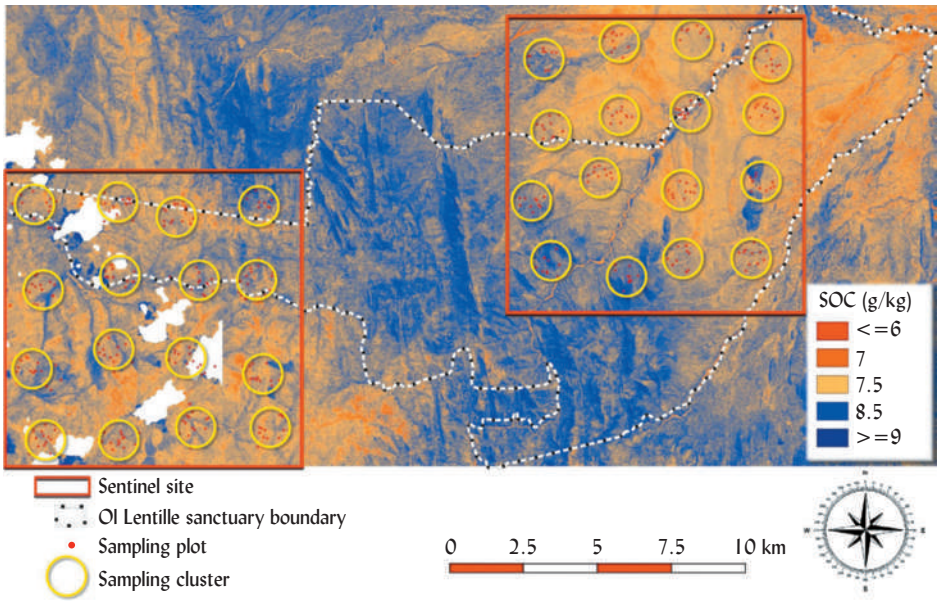

Figure 19.35 *Digital soil mapping to predict the spatial distribution of a soil property, organic carbon concentration, in a rangeland preserve in Kenya. The base map display included the preserve boundaries, land relief (hill-shaded DEM) and locations of soil profile samples analyzed. The doubly nested random sampling design featured two large sentinel sites (red outline), each with 16 sampling clusters (yellow circles) inside of which 10 sampling plots (red dots) were randomly located. The resulting digital map of soil organic C concentrations shows low carbon (red colors) in the sandy river courses and higher carbon (blue colors) on the more densely forested hills.* [Image courtesy of Tor Vågen, World Agroforestry Centre; concepts based on Vågen et al. (2012) and Winowiecki et al. (2015)]

Making a truly digital soil map of any region—let alone of the world—is a huge challenge. It pushes the envelope on geographic information technologies. It requires the fusion of soil and remotely sensed datasets, the application of sophisticated spatial models and advanced mathematics, and a deep understanding of soils.

19.9 GIS, GPS, AND PRECISION AGRICULTURE[8]

Large scale farming can be improved by combining several advanced technologies: (1) the GPS of Earth-orbiting satellites (see Section 19.3) that can precisely monitor or control vehicle movements, (2) computerized GIS capable of making detailed maps that integrate information about many soil properties, and (3) variable rate technologies that allow farm equipment to alter the rate of fertilizer, seed, or chemical delivery on the go. The combined technology, sometimes referred to as "precision farming" or "site-specific agriculture," allows farmers to make the application of nutrients and other inputs more tailored to each part of a field than was previously practical for large farming operations.

Soil properties in one part of a farm field may differ markedly from those in another part of the same field (Figure 19.36), with each part requiring management systems quite different from the others for optimal results. However, until the advent of the precision farming technologies, the best farmers could do was manage a whole field according to the average conditions, aiming for optimal average returns from their inputs. Managing for the average condition is likely to be inherently inefficient, failing to remove the soil constraints in one area of a field, while in another area providing excessive inputs that may lead to environmental contamination.

Where small-scale variability exists, the actual level of fertility at most spots in the field is likely to be either considerably higher or lower than the average soil test value for the field. To visualize the effect of the unaccounted-for variability, consider an analogy with shoe sizes. Fertilizer recommendations based on a field average may fit the needs of the soil about as well as buying size 6 shoes for everyone in a family because it happens to be the average shoe size for that family. Several technological developments have made it much easier than in the past to detect, map, and manage small-scale soil variability (see Sections 19.3 and 19.8).

[8]For an assessment of the future of site-specific agriculture, see Dobermann et al. (2004).

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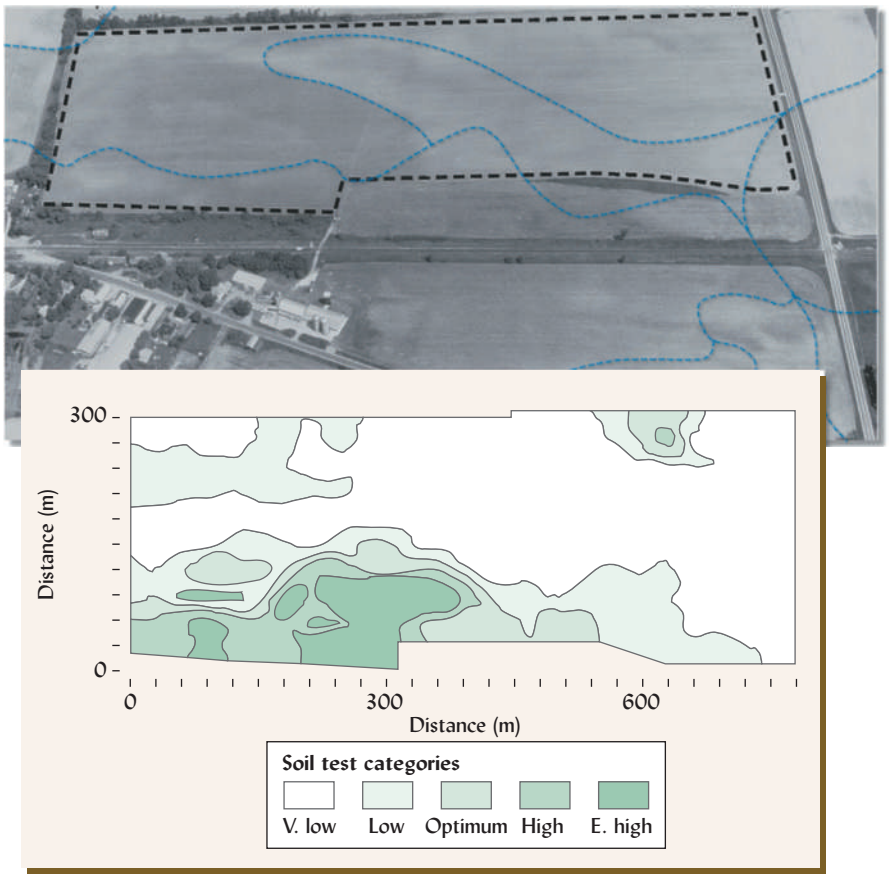

Figure 19.36 *An oblique air photo* (top) *of a farm in central Wisconsin, USA. The 22-ha field outlined by the heavy dashed line was studied in detail to make a map* (bottom) *of the spatial variability of available (soil test) potassium. The map was computer-generated using soil test values from 199 samples (each made up of five subsamples) taken at 32-m intervals in a grid pattern across the entire field. Note that the very high potassium levels correspond with a section of the field closest to the farmstead (lower left in photo). In the past, the farmer had managed that section as a separate field and had used it to dispose of manure from the nearby barnyard. The high-potassium spot in the upper right of the field marks the location where manure had been piled a number of years prior to the study. The spatial variation in potassium levels appears to be unrelated to the soil boundaries (light dashed lines) mapped in the county soil survey report.* [From Wollenhaupt et al. (1994)]

One approach to precision farming is to divide a large field into cells in a grid pattern, each cell usually being about 1 ha in area. For example, 44 separate geo-referenced soil samples (each being a composite of about 15–20 soil cores) may be collected from a single 44-ha field (Figure 19.37). These soil samples can then be analyzed for such properties as texture, organic matter content, pH, and soil test levels of phosphorus and potassium. A computer program can then produce a map of the spatial distribution of each soil property measured. Thus, one map might show areas of low, medium, and high soil test phosphorus levels. Another map might show areas of high, medium, and low clay content, and so on. Information on other spatial variables, such as soil classification, drainage class, past management, weed density, and so forth, can be fed into the program to generate additional maps. A sophisticated computer program then integrates the information from these individual maps to create a new combined map showing the different application rates of lime, fertilizer (or other material) that are recommended for different parts of the field (see Figure 19.38).

Variable Rate Technology

For example, areas mapped as testing low in phosphorus might be slated to receive higher-than-average application rates of phosphorus fertilizer, while areas mapped as being high in phosphorus might receive no phosphorus fertilizer at all. Similarly, reduced rates of nitrogen fertilizer application might be mapped for areas of sandy soils with high leaching potential but low yield potential. The application-rate maps are then programmed into a computer on board the machine that spreads the fertilizer. The fertilizer spreader is also equipped with a GPS receiver and an associated computer that tracks the spreader's location on the map as it moves across the field (Figure 19.38). The computer then signals small motors on the fertilizer spreader to increase or decrease the rate of application, as called for on the map. Thus, the system is designed to prevent overapplication on the high-fertility areas

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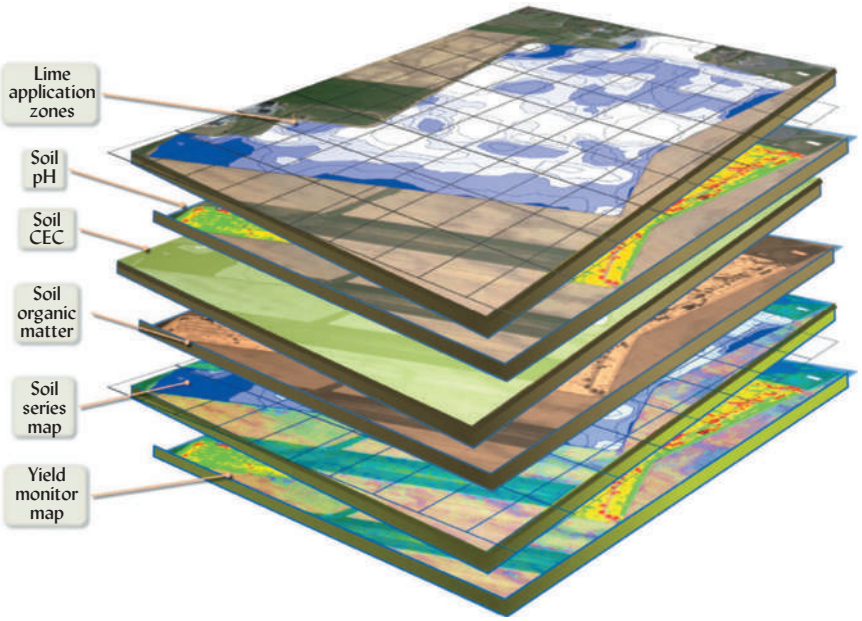

Figure 19.37 *Spatial technology used to facilitate site-specific nutrient-management systems. The Global Positioning System (GPS) can plot the location of many soil sampling and plant production sites on a grid basis within a field. A soil sample (composite of 20 cores) is taken from each cell (about 1 ha) and analyzed. With soil analysis and other data from these cells, computer programs can create maps such as the one shown here for a 44-ha field. The top map combines data from the other layers to define "lime application rate zones." Satellite GPS combined with ground station RTK positioning and computer systems can then be used to control variable-rate lime or fertilizer applicators that apply only the amounts of material called for by the soil tests and past soil management. Similar satellite/computer connections allow monitoring of crop yields when the harvest machine traverses the field. The resulting yield maps can further inform the soil management system.* (Diagram courtesy of Ray R. Weil)

(which should save money and reduce nutrient-pollution potential) and prevent underapplication on the low-fertility sites (which should make money by producing a higher yield). The total amount of fertilizer or lime added may not be greatly different from that used in the past, but application rates should be more in tune with plant needs and environmental cautions.

At harvest time, similar computerized satellite linkages are used to monitor yields in different parts of the field and to create maps showing the yield differences. The yield maps produced by GPS-equipped harvest combines are proving to be the most popular component of the entire system, as they help farmers pinpoint problem areas for investigation. Yield levels in some parts of a field, even in one that is uniform in appearance, commonly are 2–3 times as high as in other parts of the field. By overlaying the yield map on the soil variable maps, it is possible to determine the extent to which nutrient deficiencies are constraining yields. However, other problems such as poor drainage, low organic matter, or even feeding by wildlife may also come to light.

Similar to what we have just discussed for lime and fertilizer, site-specific management systems can also control insects and weeds and modify plant seeding rates, locations, and depths, allowing precision farming to manage land on a site-specific basis, rather than on a whole field basis. Such computerized GPS-based systems are expensive in terms of equipment costs and costs to collect all the requisite information, especially the many grid sample analyses needed. The technology may not be economically viable for all farms, but its use is spreading, particularly among custom operators with computer expertise and the appropriate equipment. Precision farming using the GPS–GIS combination may help assure that fertilizers, manure, and pesticides are used only where they are needed to enhance plant production. The development of portable spectral sensors and other on-the-go sensing (Section 19.3) may lead to an even more efficient and affordable precision farming system that eliminates the expense of GPS, GIS, and grid soil sampling. Such sensors may be able to respond to changes in soil properties and control application equipment in real time and on the go.

The GPS guidance systems can be made considerably more precise if a ground-based reference such as a cellphone tower is used for correction. Real Time Kinematic (RTK) navigation is an even more precise technique that enhances GPS accuracy with a stationary base station receiver and a several mobile units. The RTK system uses the phase of the wave signals from the satellites, rather than the information content, to determine

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Figure 19.38 *Use of GPS technology in precision or site-specific farming.* (Left) *View from the cab of a fertilizer spreading machine that is GPS-guided and capable of changing the rates of application as required by the computer map as it drives across a field. This type of farming is also known as Prescription Farming.* (Upper right) *A map of the same field showing the lime required to raise the soil pH to 6.5 as determined from samples collected in 1-ha cells.* (Lower right) *This map of corn yields throughout a 22-ha field was generated by a harvesting machine equipped with a yield monitor and a GPS receiver. Each dot on the map was generated as the monitor recorded the yield of corn every few meters while the machine worked up and down the field. Each yield measurement was associated with a map position determined by the GPS. An agronomist can then check the red areas where yields were low to ascertain the cause and design measures to alleviate the problem in those spots.* (Photo of in-cab computer enhanced to show detail, courtesy of Ray R. Weil, maps courtesy of Hoober, Inc)

position. Equipment navigating with RTK can automatically move within 1 cm of the programmed path, allowing very precise planting patterns and cultivation of weeds without injuring crops.

19.10 CONCLUSION

Making soil surveys is both a science and an art by which many soil scientists apply their understanding of soils and landscapes to the real world. Mapping soils is not only a profession; many would say that it is a way of life. Working alone outdoors in all kinds of terrain and carrying all the necessary equipment, the soil scientist collects ground truth to be integrated with data from satellites and laboratories. The resulting soil maps and descriptive information in the soil survey reports and databases are used in countless practical ways by soil scientists and nonscientists alike. The soil survey, combined with powerful geographic information systems, enables planners to make rational decisions about what should go where. One challenge for soil scientists and concerned citizens is to develop the foresight and fortitude to use criteria in the GIS planning process that will help preserve our most valuable soils—not hasten their destruction under shopping malls and landfills.

Likewise, solving the global environmental problems our planet faces will require application of the best science and information about what is happening where. Much of the work to find solutions to problems like greenhouse gas emissions, soil degradation, pollution, and water conservation entails the development of computational models that can simulate ecosystems processes. To be effective tools, these models need soils data that are "geographically continuous, scalable, and which includes uncertainty estimates." Digital soil maps are being developed to provide that data and allow soils information to be integrated with other ecosystem properties.

Similar data processing techniques are used to integrate soil spatial data with agricultural machinery to optimize farm management.

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STUDY QUESTIONS

1. What is the principal difference between a *soil association* on one hand, and a *catena* on the other? What is the difference between a *lithosequence* and a *toposequence*?
2. What is the main purpose of digging soil pits as part of making a soil survey?
3. Describe the kinds of information a soil mapper may use in deciding where to drill into the soil with an auger to bring up subsurface samples for study.
4. How can the GPS be used in a GIS?
5. What are the advantages of using aerial photos as a map base in making a soil survey?
6. For the region in which you live, describe some kinds of information that you would expect to be able to obtain from satellite imagery.
7. Assume that you have two wall maps, each approximately 1 m wide × 0.70 m tall. One is a map of Canada, and the other is of a ranch in California. Which map is the large-scale map and which is the small-scale map? If the ranch is roughly 20 km from east to west, what might be the approximate scale for its map?
8. A soil mapper drew a boundary around an area in which he made six randomly located auger borings, two in soil *A*, with an argillic horizon more than 60 cm thick and strong brown in color, and the other four in soil *B*, with a somewhat lighter brown argillic horizon between 50 and 70 cm thick. Other soil properties, as well as management considerations, were similar for the two types of soils. Would the map unit delineated likely be a *soil association*, a *soil consociation*, or a *soil complex*? Explain.
9. Assume you are planning to buy a 4-ha site on which to start a small orchard. Explain, step by step, how you could use the soil survey to help determine if the prospective site was suitable for your intended use.
10. If you were hired by a state government to produce a GIS-based map showing where investments should be made to protect farmland from suburban development, what "layers" of information would you want to include in the GIS?
11. Try to produce the map shown in Figure 19.19 by visiting websoilsurvey.nrcs.usda.gov/app/. Hints: the location is about 4 miles due south of the town of Bel Air, Maryland (enter these as the city and state under the "Navigate by Address" tab). Be sure to study the instructions available on the website.
12. Imagine you are hired as a community planner. Suggest criteria for selection of land suitable for recreational use, municipal buildings (town garage, offices, school), and sewage treatment. What "layers" of information would you seek, and which would be needed for each area of land to be developed?
13. What is DEM and how is it used in mapping soils (polygons) and soil properties (raster data)? Soil map?
14. How does an understanding of soil formation state factors relate mapping soils (polygons) and soil properties (raster data)? What state factors are most commonly relevant and why?

REFERENCES

AfSIS. 2015. "African soil information service [Online]." http://africasoils.net/ (verified 1 February 2015).

Arrouays, D., N. McKenzie, J. Hempel, A. R. d. Forges, and A. B. McBratney. 2014. *Global Soilmap: Basis of the Global Spatial Soil Information System*. CRC Press, Boca Raton, FL, p. 494.

Baveye, P. C., and M. Laba. 2015. "Moving away from the geostatistical lamppost: Why, where, and how does the spatial heterogeneity of soils matter?." *Ecological Modelling* **298**:24–38

Bruland, G. L., S. Grunwald, T. Z. Osborne, K. R. Reddy, and S. Newman. 2006. "Spatial distribution of soil properties in water conservation area 3 of the everglades." *Soil Science Society of America Journal* **70**:1662–1676.

Clark, R. N., G. A. Swayze, K. E. Livo, R. F. Kokaly, S. J. Sutley, J. B. Dalton, R. R. McDougal, and C. A. Gent. 2003. "Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert systems." *Journal of Geophysical Research: Planets* **108**:5131.

Cline, M. G., and R. L. Marshall. 1977. "Soils of New York landscapes," Information Bulletin 119, Physical Sciences, Agronomy 6, New York State College of Agriculture and Life Sciences, Cornell University.

Daughtry, C. S. T. 2001. "Discriminating crop residues from soil by shortwave infrared reflectance." *Agronomy Journal* **93**:125–131.

Dobermann, A., S. Blackmore, S. E. Cook, and V. I. Adamchuk. 2004. "Precision farming: Challenges and future directions." In T. Fischer et al. (eds.). *New Directions for a Diverse Planet: Proceedings for the 4th International Crop Science Congress, Brisbane, Australia*, 26 September–1 October 2004. www.Cropscience.Org.Au.

Doolittle, J. A. 1987. "Using ground-penetrating radar to increase the quality and efficiency of soil surveys." In W. U. Reybold and G. W. Peterson (eds.). *Soil Survey Techniques*. SSSA Special Publication No. 20. Soil Science Society of America, Madison, WI.

Doolittle, J. A., B. Jenkinson, D. Hopkins, M. Ulmer, and W. Tuttle. 2006. "Hydropedological investigations with ground-penetrating radar (GPR): Estimating water-table depths and local ground-water flow pattern in areas of coarse-textured soils." *Geoderma* **131**:317–329.

FAO. 2006. *Guidelines for Soil Description*, 4th ed. Food and Agriculture Organization of the United Nations, Rome.

FOR REFERENCE PURPOSES ONLY

Fisher, M. 2012. "Creating a global digital soil map." *CSA News* **57**:4–9. https://www.agronomy.org/files/publications/csa-news/creating-a-global-digital-soil-map.pdf.

Gesch, D., G. Evans, J. Mauck, J. Hutchinson, and W. J. Carswell Jr. 2009. "The national map-elevation," Fact Sheet 2009-3053. U.S. Geological Survey, Reston, VA. http://pubs.usgs.gov/fs/2009/3053/

Grunwald, S., P. Barak, K. McSweeney, and B. Lowery. 2000. "Soil landscape models at different scales portrayed in virtual reality modeling language." *Soil Science* **165**:598–615.

Grunwald, S., G. M. Vasques, and R. G. Rivero. 2015. "Fusion of soil and remote sensing data to model soil properties." *Advances in Agronomy*. Academic Press, San Diego, CA.

Halls, P., C. McClean, and G. Newton-Cross. 2007. *GIS for Ecologists and Environmental Scientists*. John Wiley & Sons, New York, p. 320.

Hengl, T., J. M. de Jesus, R. A. MacMillan, N. H. Batjes, G. B. M. Heuvelink, E. Ribeiro, A. Samuel-Rosa, B. Kempen, J. G. B. Leenaars, M. G. Walsh, and M. R. Gonzalez. 2014. "Soilgrids1km—global soil information based on automated mapping." *PLoS One* **9**:e105992.

Herring, T. A. 1996. "The global positioning system." *Scientific American* **270**(2):44–50.

ISRIC. 2015. "Soilinfo [Online]." ISRIC World Soil Information. Available at http://www.isric.org/ (verified 12 February 2015).

Kweon, G. 2012. "Toward the ultimate soil survey: Sensing multiple soil and landscape properties in one pass." *Agronomy Journal* **104**:1547–1557.

Legros, J.-P. 2006. *Mapping of the Soil*. Science Publishers, Enfield, NH, p. 422.

Miller, B. A., and R. J. Schaetzl. 2014. "The historical role of base maps in soil geography." *Geoderma* **230–231**:329–339.

Mulder, V. L., S. de Bruin, M. E. Schaepman, and T. R. Mayr. 2011. "The use of remote sensing in soil and terrain mapping—a review." *Geoderma* **162**:1–19.

Riddle, R. 2015. "Soil survey of Los Angeles County, southeastern part, provisional maps (January 2015)." NRCS, MRLA Soil Survey Office Oxnard, CA.

Schoeneberger, P. J., D. A. Wysocki, E. C. Benham, and S. S. Staff. 2012. *Field Book for Describing and Sampling Soils*, version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/research/report/?cid=nrcs142p2_054184.

Soriano-Disla, J. M., L. J. Janik, R. A. V. Rossel, L. M. Macdonald, and M. J. McLaughlin. 2013. "The performance of visible, near and mid-infrared reflectance spectroscopy for prediction of soil physical, chemical and biological properties." *Applied Spectroscopy Reviews* **79**:1–120.

USDA-NRCS. 2006. "National soil survey handbook, title 430-vi." U.S. Department of Agriculture, Natural Resources Conservation Service. http://soils.usda.gov/technical/handbook/ (posted 22 March 2006; verified 20 October 2006).

USDA/NRCS. 2015a. "Web soil survey [Online]." Available by U.S. Department of Agriculture/Natural Resources Conservation Service. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (verified 1 February 2015).

USDA/NRCS. 2015b. "Official soil series descriptions (OSDS) [Online]." U.S. Department of Agriculture/Natural Resources Conservation Service. Available at http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053587 (verified 25 January 2015).

USDA/NRCS. 2015c. "National soil survey handbook, title 430-vi. [Online]." U.S. Department of Agriculture, Natural Resources Conservation Service. Available at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054242 (verified 1 February 2015).

Vadeboncoeur, M. 2003. "Using GIS to prioritize land for management in the conservation of a rare species." Brown University. http://envstudies.brown.edu/thesis/2003/matthew_vadeboncoeur/ (posted 16 November 2004; verified 15 June 2006).

Vågen, T.-G., F. Davey, and K. Shepherd. 2012. "Land health surveillance: Mapping soil carbon in Kenyan rangelands." In P. K. R. Nair and D. Garrity (eds.). *Agroforestry: The Future of Global Land Use*, Vol. 9. Springer, Netherlands, pp. 455–462

Winowiecki, L., T.-G. Vågen, and J. Huising. 2016. "Effects of land cover on ecosystem services in Tanzania: A spatial assessment of soil organic carbon." *Geoderma* 263:274–283.

Wollenhaupt, N. C., R. P. Wolkowski, and M. K. Clayton. 1994. "Mapping soil test phosphorus and potassium for variable rate fertilizer application." *Journal of Production Agriculture* **7**:441–448.

Zwicker, S. E. 1992. *Soil Survey of Bureau County, Illinois*. USDA Natural Resources Conservation Service, Washington, D.C.

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20 Prospects for Soil Health in the Anthropocene

Senegalese women nurture their family's health through soil health. (Ray R. Weil)

. . . it is impossible to care for each other more or differently than we care for the earth.
—WENDELL BERRY

We conclude our exploration of soils as we began, with the observation that among the millions of life forms on our planet, one species, the human species, now exerts a dominant influence over the ecosystems and biogeochemistry of Earth. The imprint of human activity is found everywhere—from the composition of the atmosphere to the temperature of the oceans. Soils in the planet's most remote places now hold traces of radioisotopes from nuclear devices and xenobiotic compounds from chemical industry; around the globe soils exposed by tillage and construction erode at rates more than 100 times as fast as before they were touched by human beings. Over vast areas of the continents soils now exhibit plow layer Ap horizons and many contain less than half of their original supplies of organic matter. Rice culture has created millions of hectares of artificial wetland soils, mainly in the subtropics. while artificial drainage has destroyed millions of hectares of natural wetlands, mainly in the cooler regions. Landfills and burial grounds have altered surficial geology in countless locations. Because of these and many other changes, scientists now believe that sometime during the past century or so, the planet slipped beyond the Holocene Epoch and into a geologic epoch that many are calling the Anthropocene (the age of humans).[1]

We belong to the first generations of humans to see an image of our whole globe from the vantage point of distant space (opening photo for Chapter 1). Perhaps that view has inspired us to gradually recognize that the actions of each country, each community, and even each individual have global implications, whether those actions relate to politics, to markets, or to soils. Changes in soil productivity in one area affect food security and prices, as well as biodiversity and water quality, in both nearby and distant places. Previous chapters have detailed many examples. Biofuels initiatives in Europe may lay bare to erosion the soils of Indonesian rainforests. Wind erosion in China may pick up soil particles that are soon detected in rain falling on the west coast of North America. Salts, nutrients, and pesticides draining from soils in one nation can make the water unfit for use in another nation downstream.

This growing awareness of global interconnectedness is paralleled by the growing acceptance of the ***ecosystem*** concept as the prime basis for decisions regarding natural-resource

[1]For an examination of the geological stratigraphic evidence for the continuing, cross-time scale (*diachronous*) human impact on the surface of the Earth and the resulting lower geologic boundary dividing anthropogenically modified layers and natural geological deposits, see Edgeworth et al. (2015).

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management. This concept recognizes that biological communities interact with each other and with the environment at all scales, from the global terrestrial ecosystem to the ecosystem of a roof-top garden or a compost pile. Furthermore, components of one ecosystem may be impacted by processes in other ecosystems. For example, chemicals from an urban ecosystem's sewage plant or an agroecosystem's overfertilized field may adversely impact an estuary ecosystem many kilometers downstream.

Soils are integral components of all terrestrial ecosystems, whether urban, agricultural, forest, marsh, or grassland. The ecosystem approach continually reminds us of the interactions among physical, chemical, and biological components, as well as between the aboveground and belowground portions of our environment. We cannot clear forest or rangeland, lime a soil, add a new irrigation scheme, or apply municipal or industrial wastes to a soil without influencing that soil and its complement of microorganisms, plants, and animals. Likewise, how we manage plant communities influences the long-term stability and quality of the soils in which they grow.

In previous chapters we explored soil processes that occur in various ecosystems, and actions that individual land users might take to influence these processes. We now turn to the global implications of local and personal decisions about how we use the land, what food we choose to eat and how we grow it, where and how we choose to live, what we buy, how we generate our energy, and how we treat the life cycle of our belongings. All these decisions—at both personal and policy levels—affect the quality and health of the soil—which in turn affects the well-being of all of us and our coinhabitants on this planet.

20.1 THE CONCEPTS OF SOIL HEALTH AND SOIL QUALITY[2]

People have traditionally evaluated soils using adjectives such as "good," "bad," "worn-out," "fertile," or "infertile." In recent years, scientists and land managers have needed better tools with which to understand and evaluate the processes that improve or degrade soils, including the impacts of alternative management practices on the overall fitness of soils to carry out their functions. They also recognized the need to find simple, integrative means to communicate these impacts to land users.

Soil Health

To assist in taking this holistic view of soil improvement or degradation, soil scientists have developed the concepts of **soil health** and **soil quality** (Figure 20.1). Although these terms have often been used synonymously, they actually involve two distinct concepts. The term *soil health* refers to self-regulation, stability, resilience, and lack of stress symptoms in a soil *as an ecosystem*. Soil health describes the biological integrity of the soil community—the balance among organisms within a soil and between soil organisms and their physical and chemical environment. Chapter 11 (Sections 11.11–11.14) presented many concepts relevant to soil health.

In many cases it is easy to observe differences in soil health that result from the way we treat our soils. The two photos in Figure 20.1 show shovelfuls of the same type of soil dug within a few meters of each other in semiarid Texas, USA. The shovelful of soil from a remnant prairie was easily dug, crumbly, and had many small visible arthropods scurrying about. The shovelful of soil from an adjacent cotton field was very difficult to dig, was almost as hard as a rock and showed no visible signs of life. Compared to the unhealthy cotton field soil, the healthy soil under perennial prairie vegetation would be expected to better resist wind erosion, have a greater capacity to quickly absorb rainfall, lose much less nitrogen by leaching,

[2]The term *soil quality* was first used by Alexander (1971). For reviews of the soil quality concept and issues, practical means to use this concept in the field, and approaches to developing soil quality indices, see Chemnitz and Weigelt (2015); Lehman et al. (2015b); Shukla et al. (2006).

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Figure 20.1 *Easily observable differences in soil health. The two photos show a Raymondville soil (Vertic Calciustolls) in semiarid Texas, USA.* (Left) *A shovelful of soil from a remnant prairie.* (Right) *A shovelful of soil from a conventionally tilled agricultural field producing cotton and sorghum. The dramatic deterioration in soil health is reflected in the visible change in soil structure and color (both soils were dry). The prairie soil* (left) *was easily dug, crumbly, and had many small arthropods scurrying about. The plowed cotton field soil was very hard to dig, behaved almost as a consolidated rock and showed no visible signs of life. Other more difficult to observe or measure soil quality indicators, from enzyme activities to water holding capacity, would also likely differ between the two soils.* (Photos courtesy of Ray R. Weil)

assimilate and cycle nutrients in plant residue more quickly, and be less easily compacted by animal or vehicular traffic. Furthermore, it would do all these things without the application of expensive inputs. Measurements of many quantitative soil properties, from enzyme activities to aggregate stability would likely also differ between the two soils and, if measured, could serve as indicators of soil health and soil quality.

The utilitarian concept of *soil quality* is more commonly used in the scientific literature and actually preceded the concept of soil health (Figure 20.2). The term *soil quality* is best applied to a soil *as a component of a larger ecosystem* that supports plant growth, regulates water flows, and so forth. *Soil quality describes the properties that make a soil fit to perform particular functions* in support of the six broad ecological roles of soils introduced in Sections 1.1–1.7. Exactly what constitutes a high-quality soil may depend on which of these roles is under consideration—in other words, the intended use or the goal of soil management must be taken into account. For example, a soil well suited to serve as an engineering medium (say, for a building foundation) may not be well suited to support plant growth. In this chapter we will emphasize three broad functions for which soil quality is most commonly managed: (1) plant productivity, (2) assimilation and recycling of waste materials, and (3) environmental protection of water and air quality.

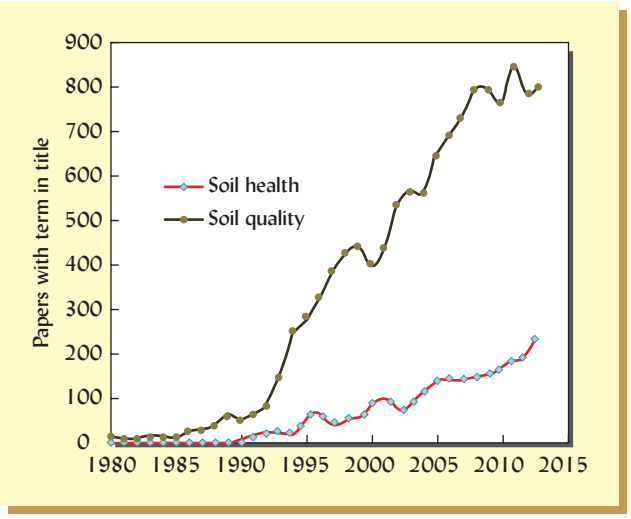

Figure 20.2 *Scientific publications on the concepts of soil quality and soil health began to be seen during the 1980s and 1990s, respectively. Growing interest in both concepts is evidenced by the increasing numbers of scientific papers published annually with these terms in their titles.* (Data obtained using Google Scholar®; graph courtesy of Ray R. Weil)

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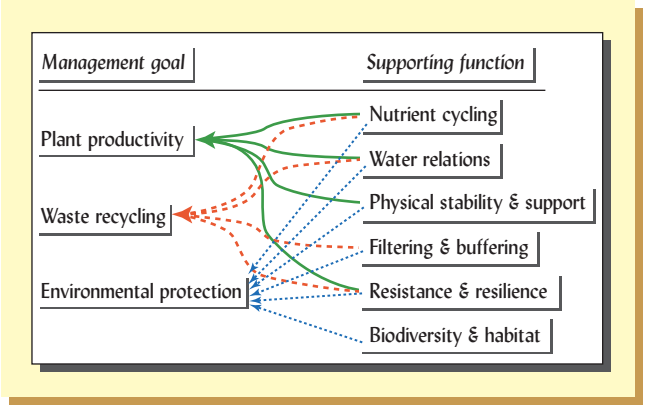

Figure 20.3 *Examples of broad soil management goals and more specific soil functions that support these goals. The plant productivity management goal aims to maximize the quantity and quality of desired plant production (crops, forage, timber, or native vegetation). The waste recycling goal aims to use the soil efficiently as a means to safely and beneficially deal with manure, sewage sludge, effluent, or other "wastes." The environmental protection goal aims to detoxify, immobilize, or isolate potential contaminants to protect air and water resources and the terrestrial food web.* [Modified from Andrews et al. (2004)]

Soil Quality in Relation to Management Goals

The management goal of plant productivity is to maximize the growth and quality of desired plants. For a farmer the desired plant production might be marketable crops, for a rancher it might be palatable forage, and for a wildlife manager it might be habitat vegetation. The management goal of waste recycling aims to use the soil efficiently as a means to safely and beneficially deal with manure, sewage sludge, or other "wastes." The goal of environmental protection aims to detoxify, immobilize, or isolate potential contaminants so as to protect food webs and enhance (or at least maintain) the quality of soil, water, and air resources. The relationship between these broad management goals and more specific soil functions is illustrated in Figure 20.3. In this context, soil quality describes the capacity of a soil to perform a particular set of functions that are required to meet a given management goal.

For example, from Figure 20.3 we can surmise that a forest manager aiming to maximize timber production would assess soil quality with regard to the capacity of the soil to perform four functions: (1) cycle nutrients—provide essential plant nutrients at appropriate times and amounts; (2) regulate water—absorb, store, and release water to plant roots; (3) provide physical support and maintain stability; (4) exhibit resistance and resilience functions (see Section 20.2) that minimize the degree and duration of impacts from major disturbances such as fire or compaction.

Each of the six specific functions shown in Figure 20.3 is associated with certain biological, chemical, and physical soil processes. Examples of such processes include the maintenance of plant-available nutrients in the soil solution, the leaching of pollutants through the soil to groundwater, the erosion of soil by wind or water, and the exchange of gases with the atmosphere that influence the soil's ability to perform. It is not always possible to measure directly the rates of these processes, but we can readily measure specific soil properties that are indicative of these rates. We can also use these measurements in simulation models to predict future changes in process rates and, in turn, soil quality. The properties measured are termed *soil quality indicators*.

Soil Quality Indicators

Table 20.1 illustrates a suggested dataset of indicator properties for the determination of soil quality in relation to the six functions described in Figure 20.3. For example, in the case of the nutrient-cycling function (that supports the plant productivity management goal), the soil quality indicators would include such measurable properties as potentially mineralizable nitrogen (PMN), soil test phosphorus level, soil pH, cation exchange capacity (CEC), and soil depth, among others.

A particular management goal or ecological role involves several soil functions; each function may involve several processes; and each process may be associated with several biological, chemical, and physical indicator properties. Therefore, the number of properties measured to assess soil quality may be a dozen or more, many of which can be measured on the

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Table 20.1
SELECTED BIOLOGICAL, CHEMICAL, AND PHYSICAL INDICATOR PROPERTIES FOR DETERMINING SOIL QUALITY
The soil ecological functions are further explained in Figure 20.3 and some of the listed indicator properties are evaluated in terms of soil quality score in Figure 20.5.

Most closely associated soil ecological functions								
Nutrient cycling	Water relations	Stability-support	Buffering-filtering	Resilience-resistance	Biodiversity habitat	Property symbol	Property description	Related book sections
						Biological		
X				X	X	MI	Maturity index of nematode trophic levels	Sections 11.2, 11.6
X			X	X	X	MFD	Meso-fauna diversity	Sections 11.2
X	X	X	X	X	X	AD	Earthworm counts	Sections 11.2–4
X				X	X	qCO_2	Respiration (per unit microbial biomass)	Section 20.8
			X		X	MBC	Microbial biomass carbon	Sections 12.2, 20.8
X						MBP	Microbial biomass phosphorus	Sections 14.4, 20.8
X			X			PMN	Potentially mineralizable nitrogen	Section 13.3
X				X	X	EZ	Enzyme activity (dehydrogenase, etc.)	Sections 11.8, 11.9
X			X	X	X	MFD	Microbial functional diversity	Sections 11.8–9, 11.14
X			X	X	X	MGD	Microbial genomic diversity	Box 11.2
						Chemical		
X	X			X	X	Active C	$KMnO_4$ oxidizable C (POXC)	Sections 12.2, 12.6
X			X		X	Soil test P	Available phosphorus by soil test	Section 16.11
X			X	X		P_{sat}	Saturation of P fixing capacity ((Al+Fe)/P)	Section 16.12
X			X		X	Soil test K	Available potassium by soil test	Section 16.11
X			X	X	X	Soil pH	Soil pH (in 1:1 water solution)	Section 9.5
	X	X		X	X	EC	Electrical conductivity	Section 10.4
X	X	X	X	X	X	SAR	Sodium absorption ration	Section 10.4
X	X	X	X	X	X	TOC	Total organic carbon	Section 12.6
X			X	X		CEC	Cation exchange capacity	Section 8.9
						Physical		
X	X	X	X	X	X	AGG	Aggregate stability when wetted	Section 4.5
X	X	X		X	X	D_b	Bulk density	Section 4.7
X	X	X	X	X	X	Depth	Depth to root limiting layer	Sections 5.9, 17.2
	X		X	X	X	AWC	Plant-available water-holding capacity	Sections 5.4, 5.8
	X	X	X	X		*S*	Infiltration capacity (sorptivity)	Section 5.6
X	X	X	X	X	X	SC	Surface crusting	Section 4.5

Based on concepts in Andrews et al. (2004); Eigenberg et al. (2006); Karlen et al. (2006); Lehman et al. (2015a); Weil et al. (2003). For many of the methods, see Doran and Jones (1996).

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Figure 20.4 *Using a soil quality kit in the field. The three different cylinders are for measuring: (a) soil respiration rate, (b) infiltration capacity, and (c) bulk density.* (Photo courtesy of Ray R. Weil)

spot in the field (Figure 20.4). Each of these measurements must be *interpreted* with regard to its implications for the soil functions under consideration. For example, if the bulk density is measured as 1.5 Mg/m^3, we must ask "is this too high, too low, or just right?" to facilitate the functions of regulating water, providing habitat, and so on. For some indicators (e.g., soil organic matter) higher values may be more desirable, for others (e.g., bulk density) lower values are better, and for still others (e.g., soil pH) there may be an optimum value, above or below which soil function suffers.

Assessing Soil Quality

To provide an overall assessment that will facilitate the comparison of soil quality from one soil to another, some way is needed to integrate many indicator properties. This task is made more complex by the fact that the measurements are expressed in many different kinds of units such as mg/kg, dS/m, $cmol_c/kg$, or Mg/m^3. To arrive at a single number that can be used to compare one soil to another, we can calculate a soil quality index (SQI) that integrates the many kinds of data collected. Soil scientists have created scoring curves that are used to give each indicator measurement a unitless score ranging from 0 (nonfunctioning) to 10 (optimal functioning). Some examples of typical scoring curves are shown in Figure 20.5. It should be emphasized that many of these scoring curves depend on the types of soils, plants, or conditions involved. For example, the scoring curve shown for soil pH implies an optimum between pH 6 and 7. While this may be applicable to productivity for most agronomic crops, the optimum for crops on Histosols, or for certain forest plants on mineral soils, might be closer to pH 5 (see Section 9.7).

In any case, assuming appropriate scoring curves are available for use, scores for the various indicators are then averaged, thus integrating all the measurements into a single number—the SQI. If it is known that some indicators have a greater influence than others on the evaluated soil functions, the scores can be multiplied by a weighting factor before they are averaged. The example in Box 20.1 illustrates the process of determining a soil quality index by this method. Figure 20.6 shows how long-term land use can influence the soil quality index.

Time- and Place-Sensitive Functions

The relative importance of different soil functions and the weights given them may change as society's perceptions evolve. This is illustrated in Table 20.3, which shows how in 1900 food

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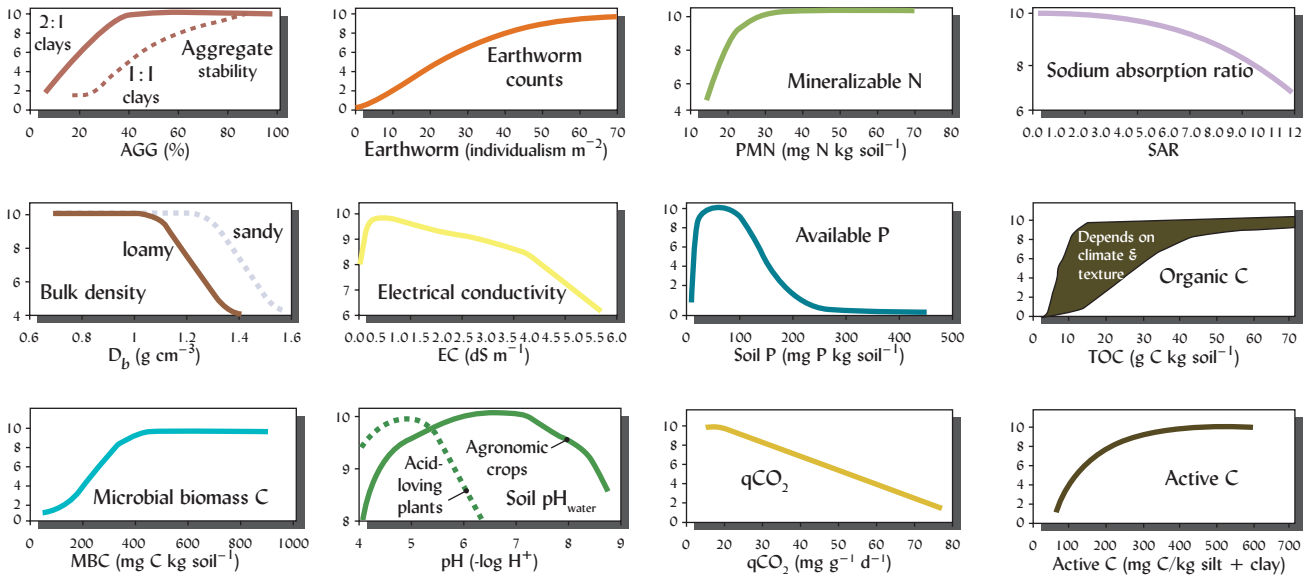

Figure 20.5 *Scoring algorithms for 12 soil quality indicator properties that can be used to calculate a soil quality index (SQI). Once each soil property has been measured on soil samples (values on the x-axes) then curves like those shown are used to extrapolate or compute a unitless scoring value (y-axes) for each property. For example, using the scoring curve for electrical conductivity (EC), a soil with EC measurement 0.5 dS m^{-1} would be given a score of 10 (best quality). Adding these scores together to create an index value integrates a wide range of chemical, physical, and biological soil properties. This SQI can then be used to assess or predict the capacity of different soils, or similar soils under differing management, to perform ecological functions. The scoring curves shown here are generalized to illustrate typical conditions. The relationships may differ somewhat among locations, and in some cases among plant species considered.* [Graphic courtesy of Ray R. Weil, partially based on materials in Andrews et al. (2004)]

BOX 20.1

CALCULATING A SOIL QUALITY INDEX FOR PLANT PRODUCTIVITY

Table 20.2 provides an example of how, if suitable measurements of soil properties were made, a soil quality index SQI for the plant productivity management goal could be derived using the information in Figures 20.3 and 20.5 and Table 20.1. Four functions of the soil supporting plant productivity are depicted: (1) *nutrient cycling*, (2) *water regulation*, (3) *physical stability*, and (4) *resilience and resistance*. In calculating the SQI, we will at first assume that each function is given equal weight. For simplicity in this example, only two indicator properties are shown for each function, therefore $n = 4 \times 2 = 8$. Others, such as those listed in Table 20.1, could have been added. Using interpretive scoring curves such as those in Figure 20.3, the measured values for the indicator properties are standardized on a common scoring scale (S) with a maximum = 10. Then the average score is calculated (Eq. (20.1)) by dividing the sum (Σ) of all the scores by the number of scores (n). This average is multiplied by 10 to provide a soil quality index that conveniently ranges between 0 and 100:

$$SQI = \frac{1}{n} \times \sum_{t=1}^{n} S_t \times 10 \qquad (20.1)$$

In some cases, there is good reason to believe that certain functions or indicators have a greater influence than others on the suitability of the soil to meet the management goal. In such cases, the indicator scores can be multiplied by appropriate weighting factors and a weighted soil quality index (SQI_w) can be calculated. For instance, assume that *nutrient cycling* was considered to be twice as important as the other functions in determining the soil's capacity to support plant growth. In that case, the indicator scores associated with nutrient cycling would be multiplied by a weighting factor (w) = 2. The SQI_w could then be calculated by summing all the weighted scores (S_{wt}) and dividing by n_w, the sum of all the weighting factors (n_w, = 10 in this example), as shown in the last two columns of Table 20.2 using (Eq. (20.2)):

$$SQI_w = \frac{1}{n} \times \sum_{t=1}^{n_w} S_{wt} \times 10 \qquad (20.2)$$

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Table 20.2
HOW INDICATOR PROPERTIES CAN BE COMBINED TO GIVE SOIL QUALITY INDICES[a]
For simplicity, only two indicator properties are given for each ecological function. An indicator (AGG in this example) may be used for more than one function. In the SQI all indicators and functions are given equal weight. In the SQI_w nutrient cycling is weighted to be twice as important as the other functions.

Management goal	Supporting ecological function	Indicator property	Measured value	Indicator score (S)	Weighting factor (w)	Weighted indicator score ($S \cdot w = S_w$)
Plant production	Nutrient cycling	Soil test P	80 mg P kg soil^{-1}	10	2	20
		PMN	20 mg N kg soil^{-1}	8	2	16
		etc.	...	...	...	...
	Water relations	AGG	30%	8	1	8
		AWC	20 g H_2O g soil^{-1}	8	1	8
		etc.	...	...	...	...
	Physical stability	AGG	30%	8	1	8
		Db	1.4 Mg m^{-3}	6	1	6
		etc.	...	...	...	...
	Resilience	TOC	25 g C kg soil^{-1}	4	1	4
		SAR	1.0	9.5	1	9.5
		etc.	...	...	...	...
		Sum of scores or factors =		61.5	$n_w = 10$	79.5
			Average of S = 61.5/8 = 7.7		**Average of S_w = 79.5/10 = 8.0**	
			Unweighted soil quality index (SQI) = 7.7 × 10 = 77		**Weighted soil quality index (SQI_w) = 8.0 × 10 = 80**	

[a]Indicator abbreviations are explained in Table 20.1. See box text for equations to calculate SQI and SQI_w. See Figure 20.5 for typical curves used to convert measurements to indicator scores.

and fiber production was paramount in people's minds and would have been highly weighted compared to the five other nonproduction functions listed. Currently, more and more emphasis is being placed on environmental quality, especially in industrialized countries where food security is reasonably assured. The broader ecological roles of soils are becoming more widely recognized. In many developing countries, however, where poverty, hunger, and even famine are still common, food and fiber production remains the soil quality issue of prime importance, as reflected in the high weight given to this function in Table 20.3.

Management-Sensitive Indicators

Some soil quality indicator properties are much more susceptible to change by soil management than are others. As indicated in Figure 20.7, properties such as soil texture, mineralogy, steepness of slope, and stoniness are inherent characteristics of the soil and are not subject to change through land management practices. While these properties are important in determining the most appropriate system to use, they will not be altered by whatever system is chosen.

At the other extreme are properties that may be subject to almost daily control so that their effect on soil quality is immediate. Examples are the soil water content as affected by irrigation and rainfall, and levels of plant-available nutrient elements that change rapidly as chemical fertilizers are applied. Also, soil density can be radically reduced by a single pass of a tillage implement or increased by a single pass of a heavy vehicle. These properties are significant for soil function, but their use in soil quality assessment is problematic since they can change so readily from day to day.

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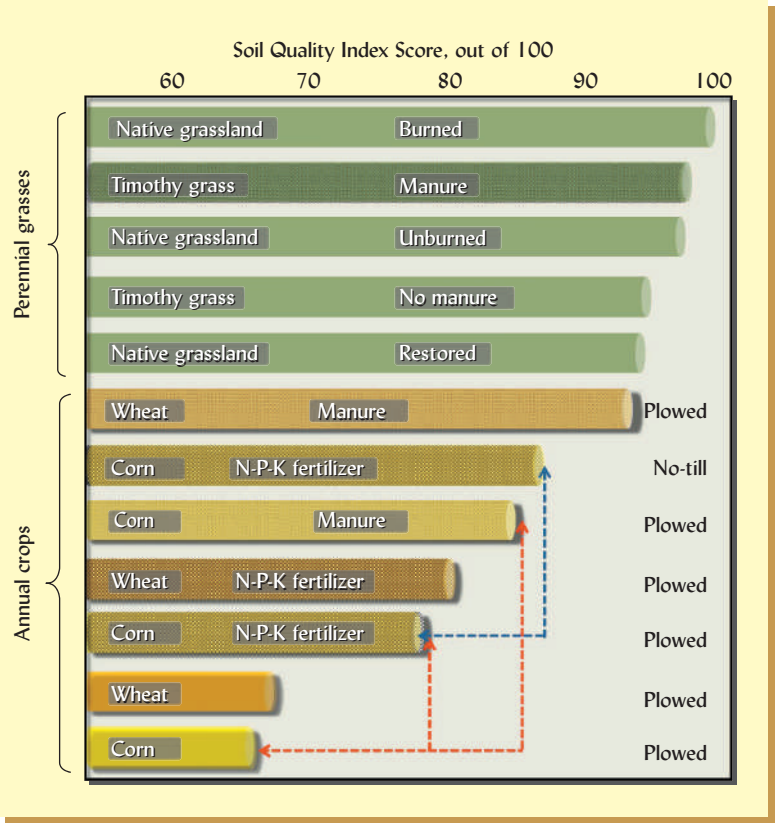

Figure 20.6 *Soil quality (by SMAF index) in plots with a long-term history of different vegetative and land management practices. The plots, located in Missouri, USA, are in the Sanborn Field long-term agricultural experiment established in 1888 and in a remnant native prairie ecosystem dominated by bluestem grasses. The soil is a Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualfs). For plots growing corn, the blue arrows indicate the negative effect of plowing (compared to no-till) and the red arrows show the positive effects of mineral fertilizer and manure. Generally, perennial vegetation (i.e., native and restored prairie or timothy) resulted in the greatest soil quality, followed by no-till and conventionally cultivated plots, with wheat outranking corn. Fertilization practices affected soil quality in the order: manure > inorganic fertilizer > unamended soil.* [Based on data in Veum et al. (2014)]

Table 20.3
How Times and Circumstances Might Influence Valuation of Soil Functions
Note the very high weights for the food- and fiber-production function in 1900 worldwide, and in developing countries today. Other functions concerned with environmental and habitat issues are much more prominent today in the wealthier countries whose people can better afford to look beyond food security.

	Probable weighting percentages		
Soil function	**Worldwide, 1900**	**Industrialized countries, 2020**	**Developing countries, 2020**
1. Food and fiber production	85	30	70
2. Resistance to erosion	3	15	10
3. Water and air quality	1	15	5
4. Food quality	5	15	5
5. Wildlife habitat	1	15	5
6. Construction and transport base	5	10	5

Intermediate between these two extremes we find properties that are subject to change only through long-term management efforts. Soil organic matter content and active carbon levels, along with microbial biomass and soil aggregation, are examples of this intermediate class of soil quality indicators. With modern molecular tools, microbial community structure and diversity are being used more frequently to assess soil health and quality. Improvement in the numbers and diversity of microbes is often associated with more efficient decomposition

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Ephemeral	Intermediate	Permanent
Changes within days or routinely managed	Subject to management over several years	Inherent to profile or site
• Water content	• Aggregation	• Soil depth
• Field soil respiration	• Microbial biomass	• Slope
• pH	• Respiration-24-hr burst	• Climate
• Mineral N	• Microbial diversity index	• Restrictive layers
• Available K	• Faunal diversity index	• Texture
• Available P	• Active C	• Stoniness
• Bulk density	• Organic matter content	• Mineralogy

Figure 20.7 *Classification of soil properties contributing to soil quality based on their permanence and sensitivity to management. Some soil properties are quite ephemeral and change readily from day to day as a result of routine management practices or weather. Others are permanent properties inherent to the soil profile or site and are little affected by management. A management-oriented soil quality assessment would focus on properties that are intermediate, but all properties tend to be mutually reinforcing.* [Modified from Islam and Weil (2000)]

and nutrient cycling. It takes years of careful management to raise the level of these properties in soils, but once they are raised, they tend to remain high for an extended period of time. These properties are important because of their major influence on soil processes such as water and air movement, soil erosion, and the generation of biodiversity. But they can be developed only if we as soil managers have at least a general understanding of the complex processes that generate them.

Farmers' Perceptions of Soil Quality

Whether or not they use terms like *soil health* or *soil quality*, farmers who work daily with soils usually note that some of their fields perform better than others. They tend to judge the quality or condition of their soils by such observable factors as the performance of crop plants, the colors associated with accumulation of organic matter, the ease of tillage, the absence of standing water after rain storms, and even the aroma of the soil. In addition, most farmers in developed countries have their soils tested for nutrient availability as a guide to what types and amounts of fertilizer to use. Since the widespread use of fertilizers and soil testing after World War II, much of the scientific effort toward improving soil management was directed at such soil testing and improving the supply and availability of mineral nutrients essential for plant growth. As a result, average soil test nutrient levels rose dramatically in intensively farmed areas such that it eventually became more common to find excessive amounts of the main fertilizer nutrients than to find deficiencies (see Sections 14.2 and 16.2).

For most of the past 150 years, the importance of organic matter management was underplayed compared to the use of fertilizers and lime. Table 20.4 presents a comparison of soils from paired fields rated as being in "good" or "poor" condition or health based on the experience of the farmers who worked with them. Note that in most cases the farmers' perceived difference in soil quality could be explained by the soil organic-matter-related properties, but not the routine fertility soil test properties. These results illustrate the dominant role that soil organic matter plays in determining the quality and performance of soils in many intensive agricultural areas in developed countries.

20.2 SOIL RESISTANCE AND RESILIENCE

Before turning to specific agroecosystems and practices that affect soil health, two other concepts relating to soil health should receive attention, namely, resistance and resilience. These terms were already used in relation to the soil functions shown in Figure 20.3. *Soil resistance* is the capacity of a soil to resist degradation when confronted with any kind of force or disturbance. A soil's capacity to resist degradation is an important component of soil health, especially as it applies to resistance to soil erosion, compaction, acidification, nutrient depletion, as well as inactivation of nutrient cycling, decomposition, and pest suppression functions. Resistance to degradation of biological function is aided by *functional redundancy*—the presence

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Table 20.4
RELATIONSHIP BETWEEN FARMER PERCEPTION OF SOIL QUALITY AND MEASURED SOIL PROPERTIES FROM PAIRS OF SOILS OF THE SAME OR SIMILAR SOIL SERIES IN THE MID-ATLANTIC REGION
All of the properties related to soil organic matter were significantly[a] better in the soils rated by farmers as having "good" soil quality, while this was true for only one of the routine soil fertility test properties.

Indicator soil property	N^b	Units	Mean for soils rated "good"	Difference	Mean for soils rated "poor"
Indicators related to soil organic matter					
TOC, total organic carbon	44	mg g^{-1}	17.6	***	14.6
MBC, microbial biomass carbon	45	mg g^{-1}	0.486	***	0.342
CMW, carbon extracted after microwave irradiation	45	mg g^{-1}	0.189	***	0.141
CRS, carbon in reducing sugars	45	mg g^{-1}	0.078	***	0.059
AGG, soil in aggregates stable when wetted	41	%	52.4	**	38.2
D,[b] bulk density	45	Mg m^{-3}	1.42	***	1.48
Indicators from routine soil fertility testing					
pH, soil pH in 1:1 water: soil slurry	41	–log (H+)	6.5	ns	6.3
Ca, calcium soil test level	40	mg kg^{-1}	1182	ns	989
Mg, magnesium soil test level	36	mg kg^{-1}	152	*	140
Ca:Mg ratio	36	-na-	4.9	ns	4.2
K, potassium soil test level	39	mg kg^{-1}	190	ns	182
P, phosphorus soil test level	41	mg kg^{-1}	184	ns	154

[a]The symbols ***, **, and * indicate 99.9%, 99%, and 95% confidence that the adjacent means are truly different by statistical analysis; ns indicates that adjacent means are not truly different according to statistical analysis.
[b]N = number of soil pairs rated by farmers.
Modified from Gruver and Weil (2007).

of multiple species of organisms that can carry out a given critical function. Such a soil is less likely to lose function when a certain species organism is decimated by a chemical toxicity or sudden environmental change.

Resistance to various types of chemical changes is analogous to the concept of buffering discussed in Sections 9.7 and 14.8. For example, the soil solution levels of potassium in some fine-textured soils high in hydrous micas are not seriously affected by the removal of this element in harvested crops. The potassium extracted from the soil solution by plant roots is quickly replenished from exchangeable and nonexchangeable forms found in the clay and silt fractions of these soils. In other words, the soil resists change, a characteristic not found in most sandy soils that lack significant levels of exchangeable and nonexchangeable potassium.

A second important concept bearing on soil health and quality is that of *soil resilience*, or the capacity of a soil to rebound from changes stimulated by disturbances or external forces. A soil under natural forest or grassland vegetation is disturbed when the land is cleared for cultivation, and properties such as organic matter content, organic matter quality, and aggregate stability all decline, thereby reducing soil quality and subsequently, soil health. If, however, the land is turned back to nature, or if other sustainable conservation systems of soil management are utilized, the soil will begin to recover and regain some of its lost properties.

The degree to which recovery takes place and its speed in doing so are measures of soil resilience, a vital component of soil health. Figure 20.8 illustrates how the functioning of four different soils might respond to a disturbance. The disturbance could be any acute change. Examples of possible disturbances include physical compaction during timber harvest, partial

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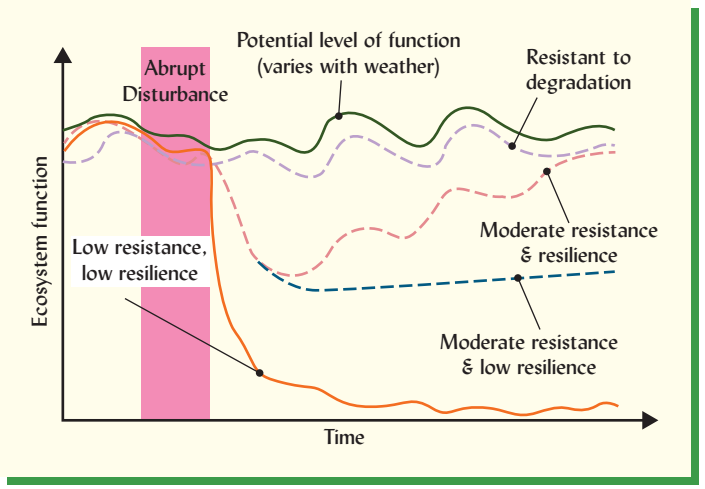

Figure 20.8 *Resistance slows down change caused by a disturbance (wildfire, compaction, landslide, erosive storm, etc.), while resilience mechanisms help the soil quickly recover from negative effects of the disturbance. The graph shows how disturbance affects the functioning capacity (plant productivity, water storage, or litter decomposition, etc.) of four soils differing in resistance and resilience. One soil (orange line) with low resistance to change, functions very poorly after the disturbance. It also has low resilience and so remains nonfunctional over time. In contrast, another soil (pink dashed line) exhibits moderate resistance and moderate resilience. Its function is partially diminished by the disturbance, but because of resilience, eventually recovers to pre-disturbance levels.* [Based on concepts in Seybold et al. (1999) and Herrick et al. (2013). Diagram courtesy of Ray R. Weil]

sterilization during a wildfire, or fragmentation of fungal networks during tillage. The respective functions impacted by the disturbance might include the ability to absorb rainwater and promote root growth, the release of nutrients by litter deposition, or the supply of phosphorus to mycorrhizal-dependent plants (see Section 11.9). In any case, a soil with high resistance would suffer only a small loss of function. Another soil with low resistance would suffer severely, but if it also has high resilience, it would rebound quickly and its functional impairment would be quite temporary.

Factors Affecting Soil Resistance and Resilience

Soil resistance and resilience are affected by both inherent and dynamic or management-oriented characteristics. For example, inherent characteristics such as texture, type of clay minerals, slope, and climate largely determine soil resistance, and have significant effects on soil resilience. These factors are the main ones accounting for the differences exhibited by certain broad soil groups in various parts of the world, with respect to their levels of resistance to productivity decline in the face of soil loss by erosion, or structural decline in the face of aggressive tillage.

Dynamic properties such as those associated with the type of vegetation, nutrient cycling, water and land management, as well as the underground community of organisms, play vital roles, especially for soil resilience. For example, properly managed vegetation can speed up the rate of organic matter buildup in a degraded soil. In other words, management can enhance soil resilience, an important component of soil quality. The significance of both soil resistance and soil resilience will be seen later on as we focus on more specific ecosystem management practices that affect soil quality.

20.3 SOILS AND GLOBAL ECOSYSTEM SERVICES

Some practices that could enhance soil health and **ecosystem services** are not adopted because they are considered to be uneconomical, that is, they fail to pay the landowner enough to justify their use. This is due in part to our economic system, which considers income as being only from products and services that can be bought or sold in the traditional marketplace. There is growing recognition, however, that such reasoning may not be valid in assessing the economic importance of ecological measures. It ignores the true value to society of many soil management practices and systems. It overlooks such services as carbon sequestration, protection of downstream water quality, enhancement of water supplies, fostering of biodiversity, protection of air quality (from dust, odors, and gaseous emissions), human disease mitigation, and even scenic beauty. Each of these services has intrinsic value, but its value may not be easily measured, nor are there always simple ways of rewarding those who enhance it.

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Just as soil health management influences the capacity of soils to perform certain ecosystem functions, so too some types of land use and ecosystems provide more or better services than others. Soil management is a key part of land management that can maximize the value of the ecosystem services provided. Figure 20.9 illustrates the relative value of eight basic ecological functions as performed by five different representative ecosystems. Too often in the past, only one or two of these functions have been properly valued or even acknowledged as management goals. The examples illustrate that not only is the choice of land use important (e.g., forest versus farm), but the type of management, including soil management, is also critical (compare the conventional farm to the ecological farm). The ecological services provided can be greatly increased with small, if any, reductions in the amount of food produced if the farm adopts such practices as no-till (Section 17.6), reduced pesticide use (Section 18.2), riparian buffers, cover crops (Section 20.4), diverse rotations (Section 16.4), and special areas devoted to habitat for wildlife and beneficial insects. Likewise, the ecosystem services provided by suburban and urban ecosystems (not shown) can be increased by such measures as green rooftops, rain gardens, permeable pavements (Section 6.2), on-site composting (Section 12.11), and increased plantings of native vegetation.

Ecological economists are attempting to measure and to express the value of ecosystem services in economic terms that have meaning to society. For example, in determining the total potential income from a forest ecosystem we should add to the timber sales the income equivalent attributable to such values as scenic beauty, watershed protection, and downstream water quality. Such methodology clearly demonstrates that the monetary income from ecosystems is often less than the "income" or societal benefit derived from other values of the ecosystem (see Table 20.5). It also suggests that the total income to be derived from soil management practices may far exceed income received from the sale of commercial products generated by these practices.

Society can recognize the benefits of various ecosystem management practices by providing incentives for using the beneficial practices or penalties for not doing so. Both penalties and incentives (often termed *green payments*) can effectively ensure that it is to the economic advantage of the landowner that appropriate soil management practices are followed, and that the loss of soil and water quality is minimized. Early examples of green payments include Conservation Reserve Program rentals in the United States (see Section

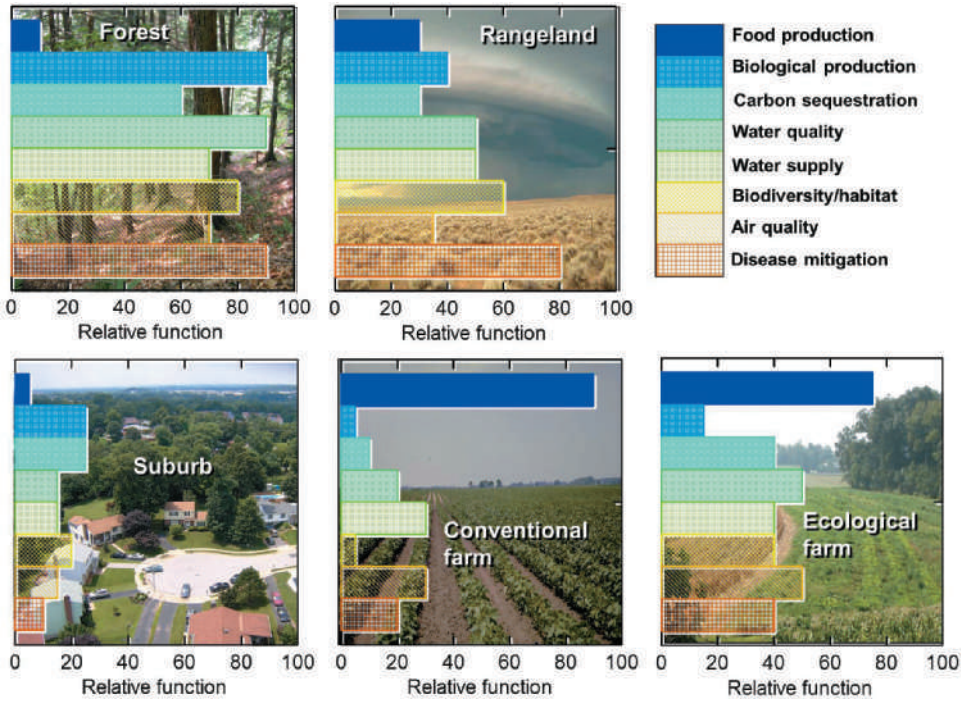

Figure 20.9 *Relative performance of ecological functions by soils in five types of representative ecosystems. For humanity to meet its needs for all the listed ecosystem services, diverse types of ecosystems are required. Soil quality interacts with ecosystem characteristics to provide these essential services to humans and other species. The graphs for the conventional and ecological farms suggest that much can be done to increase ecosystem services with only a small sacrifice in near-term food production.* (Diagram and photos courtesy of Ray R. Weil)

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Table 20.5
PROPORTION OF THE POTENTIAL INCOME FROM ECOSYSTEM SERVICES PROVIDED BY FIVE HYPOTHETICAL LAND-BASED BUSINESSES
Note that only 30–60% of the value is derived from traditional sources of income (in bold). Society will have to develop innovative political, social, and marketing means of appropriately rewarding each business for the total value it generates.

	Proportion of net income, %				
Commodity or service	**Forest plantation**	**Grazing dairy farm**	**Cattle Ranch**	**Golf course**	**Corn and soybean farm**
Milk	0	**20**	0	0	0
Grains	0	**5**	0	0	**60**
Hay/forage	5	**5**	**10**	5	0
Cattle	0	**5**	**30**	0	0
Timber	**30**	**5**	**5**	0	0
Carbon sequestration	15	10	**5**	5	12
Water filtration/collection	15	10	10	10	8
Air purification	5	5	5	5	5
Soil fertility	5	5	5	5	3
Scenic beauty	5	10	5	15	5
Recreation	**5**	5	5	**45**	5
Biodiversity	10	10	10	5	2
Salinity control	0	0	5	5	0
Medicinal plants	5	5	5	0	0

For a discussion of ecosystem values and services, see Daily et al. (2000).

17.15), and payments made to farmers by utility companies or governments in some countries for each unit of atmospheric carbon sequestered by improved soil management. Sometimes private markets do facilitate compensation for some of the ecosystem services. For example, some farmers today manage their land for both high crop yields and good wildlife habitat because they can make money from crops sales and from fees paid by sportsmen for hunting excursions.

Endangered Soils[3]

Some scientists have proposed that certain soils are so unique and so rapidly succumbing to erosion, urbanization, and other destructive processes that they need society's protection. They propose protecting these soils by designating them as *rare* and *threatened*, much as certain plant and animal species are protected by such designations. A soil would be designated *rare* if it exists over only a very limited area, while a soil might be designated as *threatened* if it is suffering from some form of degradation that is compromising its ability to function in the ecosystem. Protection from further degradation might be provided based on the value of the particular soil with regard to: (1) economic productivity, (2) ecosystem services, (3) scientific value for the study of unique soil processes and properties, (4) historic or cultural value (such as the inclusion of fossils or artifacts within the profile), and (5) simple rarity.

These and other creative political, social, and economic actions are likely to be needed in increasing measures to ensure that scientific findings such as those discussed in this book are widely utilized to maximize soil health and ecosystem services for the benefit of all.

[3]For one proposal for protecting endangered soils, see Drohan and Farnham (2006).

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20.4 USING PLANTS TO IMPROVE SOIL HEALTH

Many people who study soils do so because they are interested in managing vegetation and growing plants, whether for wildlife habitat, crops, or landscaping beauty. Much of this book is devoted to explaining how we can best manage soils to improve the growth of plants. However, the relationship can also work the other way around. We need to also know how to manage plants to improve soils. Plants, are, after all the dominant organisms in most soils. Plants are also the best tool we have for enhancing soil health.

Plants for Land Restoration

The restoration of disturbed or degraded land may require physical manipulation of the soil, such as forming terraces of steep eroded land or changing topography and permeability to restore saturated condition to a once-drained wetland. However, the key to restoration is usually the establishment of suitable vegetation for the desired ecosystem, whether that is a native grassland, a forest, or a marsh. Plants can be chosen that will enrich soils with nitrogen or promote mycorrhizal associations. Plant canopies, roots, and litter provide protection from erosion. As discussed in Section 11.9, diverse plants stimulate general biodiversity and connect above- and belowground communities. Similarly, carefully chosen agricultural plants can be used to restore soil health to abandoned urban lots and large farms, alike. This idea is bringing new life to an old farming practice—the use of cover crops (also discussed in Sections 4.7, 16.9, and 17.6).

Fundamental Advantages of Cover Crops for Soil Health

Innovative farmers around the world—but especially in Australia and North and South America—are increasingly viewing cover cropping as an important tool to manage soil health. The fundamental advantages that cover crops offer are twofold: (1) greater annual duration of vegetative resource use and function and (2) opportunities to greatly increase plant (and subsequently animal and microbe) biodiversity. On the first point, the typical corn-soybean rotation of annual crops captures environmental resources (sunlight, nutrients, water) and supports the health of the soil (covering the soil, adding carbon, providing root exudates, root signally, nutrient cycling, etc.) for only three to four months of the year (Figure 20.10). Cover crops can more than double the period of plant activity, build soil health, and allow annual cropping

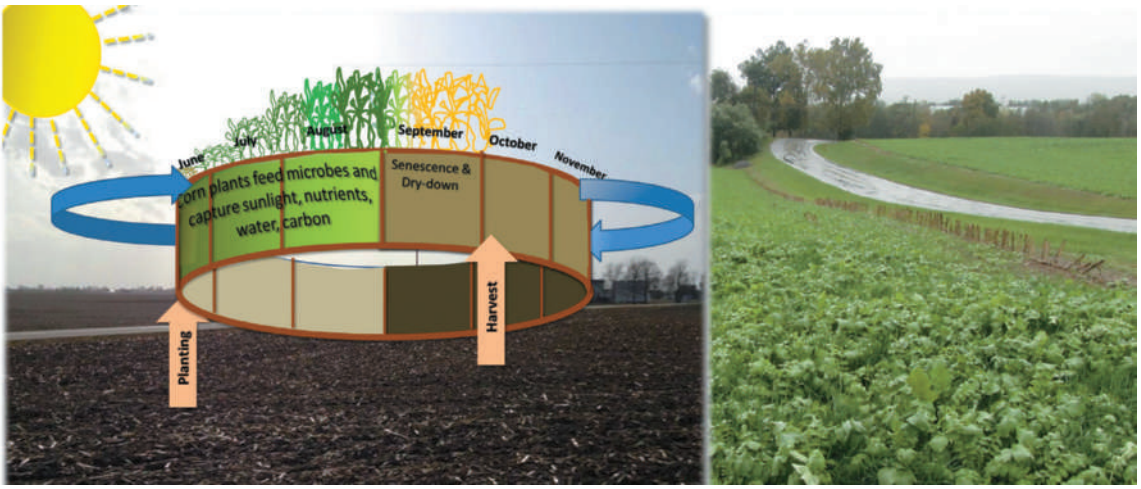

Figure 20.10 *The sun shines, the rain falls, and soil microbes work 12 months a year, but this typical U.S. corn belt farm (left) captures only three to four months of this activity. Building soil health should as much as possible occur all year round. (Right) Cover crops (such as this multispecies cover crop planted after corn silage harvest) can build soil health and allow annual cropping systems to utilize resources that might otherwise be wasted. If properly managed, cover crops may increase crop yields, decrease expensive inputs, and improve long-term soil health.* (Photos and diagram courtesy of Ray R. Weil)

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systems to utilize resources that might otherwise be wasted. If properly managed, cover crops may increase crop yields, decrease the need for expensive inputs, and improve long-term soil health.

On the second point, cover crops free the farmer from the limitations of the marketplace. That is, farmers, especially those with large-scale operations, are usually restricted to growing just a few plant species (crops) that they can produce and sell in large volume. However, since cover crops are not sold, but are grown to improve soil health, any number of species can be grown on a farm, sometimes in complex mixtures of five to ten or more species from many plant families (legumes, grasses, brassicas, composites, etc.). Finally, as many cover crops can provide quality forage at important times of year, their use offers an opportunity to reintegrate livestock with crop production, to the benefit of farmers, soils, animals, and crops alike.

Barriers to Cover Crop Use

Adding cover crops to a farming system can increase the complexity of farm management. After all, a cover crop is another crop in the rotation to plan for, purchase or save seed for, plant, and manage. Cover crop timing is critical to success. It may require special management (early maturing main crop, airplane seeding prior to main crop harvest, etc.) to get the cover crop planted early enough for optimal performance. In addition, it is important that cover crops be selected and managed carefully to avoid such potentially undesirable effects as:

- Production of seed that creates a weed problem.
- Residues that host crop insect pests or pathogens.
- Residues that immobilize N (and S and P) needed by the following cash crop.
- Incompatibility with efficient operation of certain equipment.
- Slowed soil warming and drying in spring.
- Allelopathic compounds that interfere with crop establishment (Section 12.5).
- Use of soil water that reduces supply for following cash crop.

Soil Water Impacts of Using Cover Crops

When a farm starts using cover crops many aspects of soil health and ecosystem function are affected (Figure 20.11). Some of the impacts of using cover crops are illustrated in the diagram. To show how one impact leads to another, the effects of cover cropping on soil water supply are highlighted (by blue arrows). The diagram shows that the cover crop provides soil

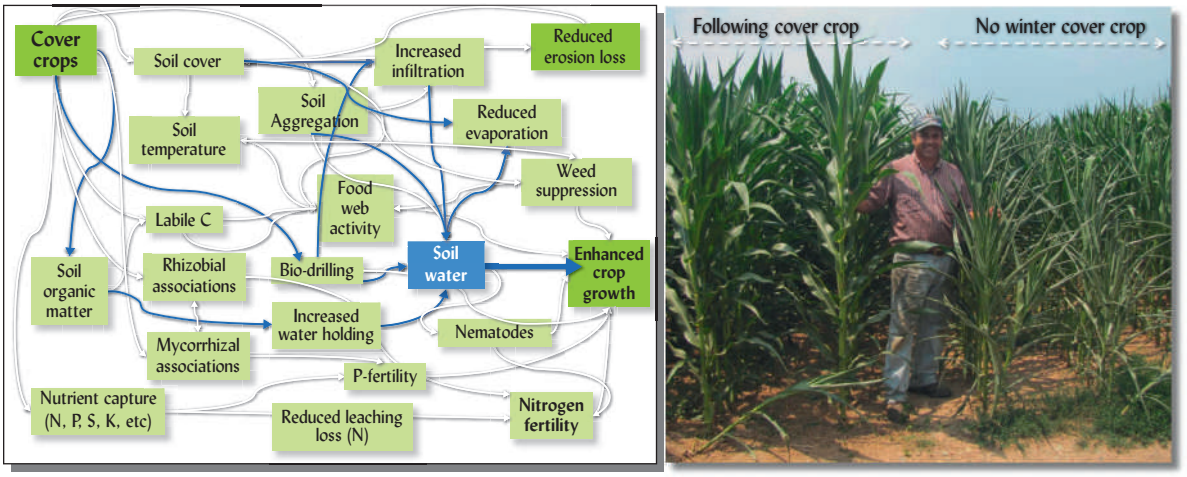

Figure 20.11 *Adding cover crop to a cropping system changes many aspects of soil health and ecosystem function. Some of the impacts of using cover crops are illustrated in the diagram* (Left)*. To show how one impact leads to another, the effects of using a cover crop on soil water supply are highlighted by blue arrows.* (Right) *Photo shows cover crop alleviation of water stress during a mid-summer dry period. Except for a cover crop established the previous autumn and terminated before corn planting, management was identical on both sides of Pennsylvanian farmer in the United States and cover crop innovator, Steve Groff, in the photo.* (Diagram and photo courtesy of Ray R. Weil)

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cover both while living and with residues after it is killed. The increased cover protects the soil surface from raindrop impact and increases the rate of infiltration, which adds to the water stored in the soil profile. The residue cover also reduces the loss of water by evaporation from the soil surface, further increasing the supply of soil water available to the main crop. If the cover crop is tap-rooted, the biodrilling action of the cover crop roots (Section 4.7) may encourage water penetration deeper into the profile and represents another way that soil water storage is increased. On the other hand, cover crops, like any plant, also transpire water from the soil and may deplete stored soil water that the main crops will need.

Several factors need to be considered when weighing the pros and cons of using cover crops in semiarid regions where main crop growth is largely limited by water stored in the soil profile. Transpiration rates are largely governed by climatic factors (Section 6.3). If the cover crop is grown during the cooler, lower evapotranspiration season, and a combination of biodrilling and surface mulch increases water storage deep in the soil profile, cover crops might conserve more water than they use up. On the other hand, if the cover crop transpires a great deal of water during warm, dry weather preceding the main crop growing season, the net result may be less stored water for the main crop to use. Unfortunately, very few measurements of these effects have been made in semiarid, multispecies cover crop systems, so scientists and land managers need to do more experimentation to innovate with cover crop use.

In humid regions where there are many opportunities to replenish soil water supply, the increased infiltration and reduced evaporation associated with cover crops usually outweighs the extra water transpired. The net result is that water conservation by cover crops may enhance main crop yields, especially if the main crop suffers periods of drought during the summer growing season (Figure 20.11, *right*).

Another resource that may be enhanced or limited by the use of cover crops is the supply of available nitrogen. As discussed in Sections 13.15 and 16.9, a cover crop species in the legume family can potentially increase, through fixation of atmospheric N_2, the soil supply of nitrogen available to the main crop. In fact legume residues may decompose so rapidly as to release their N before the summer crop is ready to take it up in large quantities. In contrast, a grass family cover crop (e.g., cereal rye, ryegrass, etc.) may compete with the main crop for soil nitrogen. Grass cover crops do so by taking up most of the soluble nitrogen from the soil during the early spring and holding it as organic–N in root and shoot residues that may be very slow to decompose and release the nitrogen back to the soil solution. In that situation, extra N fertilizer may need to be applied to maintain high crop yields (Figure 20.12). However,

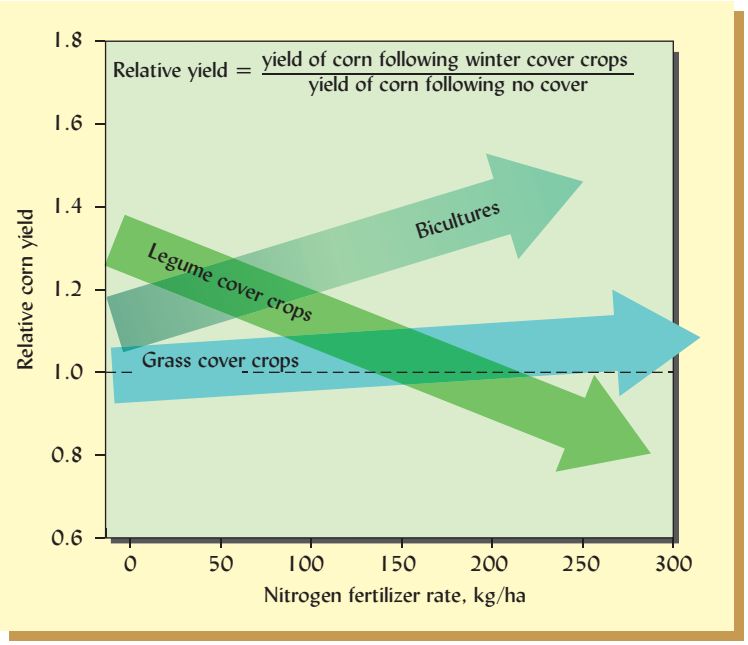

Figure 20.12 *Cover crop effects on corn yields depend on the type of cover crop species used. Legume cover crops usually increase corn yields (relative corn yield >1) only when little or no nitrogen fertilizer is used on the corn. Grass cover crops usually do not increase, and may decrease, corn yields, unless large amounts of N fertilizer are applied to overcome the tendency for grass cover crop to immobilize N. Using both types of species together (a biculture) may be the best approach that captures the N contribution of the legume and long-lasting moisture conserving mulch of the grass.* [Diagram courtesy of Ray R. Weil based on meta-analysis by Miguez and Bollero (2005)]

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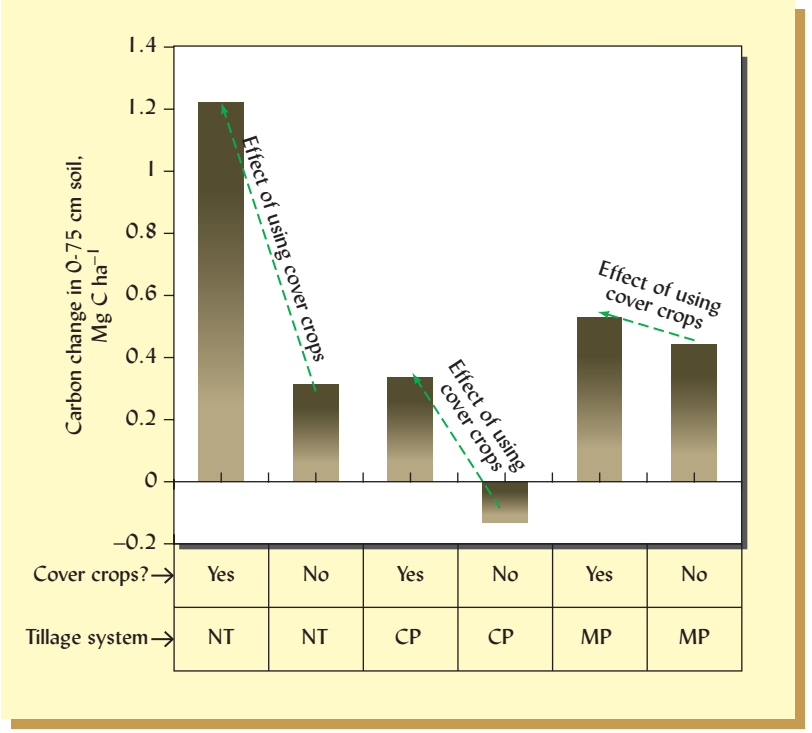

Figure 20.13 *Synergistic effect on soil health when cover crops and no-till management are combined. The data show how the accumulation of soil organic carbon (SOC) during a 12-year study was affected by the interaction of tillage practice (no-till, NT; chisel plow, disk, CP; and moldboard plow, disk, MP) with the use of cover crops. The experiment used a corn–soybean rotation on a sloping site with a moderately well-drained soil (Typic Fragiudalf). While the different combinations of tillage and cover crop use did not influence crop yields, they did alter the levels of soil erosion (no-till greatly reduced erosion) and the balance between gains and losses of carbon. The data are for the upper 75 cm of soil, below which a fragipan restricted root growth.* [Graphic courtesy of Ray R. Weil, based on data in Olson et al. (2014)]

planting species of both families in a mixed species cover crop may achieve the right balance between nitrogen conservation and nitrogen availability (see biculture arrow in Figure 20.12).

As suggested by Figure 20.10, incorporating cover crops into a system of annual crops can increase carbon sequestration by several mechanisms, including reducing the carbon losses by erosion, and increasing root residue carbon contributions. The presence of cover crops also lengthens the period of time each year that the system is converting solar energy into organic carbon. Cover crops also add food from their root exudates and their plant residues to stimulate a more active and diverse soil food web. Cover crops are especially effective in improving soil health when combined with no-till management (Figure 20.13). In addition, the analysis of hundreds of tillage system comparisons around the world suggests that the use of cover crops along with the retention of crop residues on the soil surface is important for obtaining high crop yields in no-till farming systems.

20.5 FEEDING THE HUMAN POPULATION

Since the dawn of agriculture some 10,000 years ago, people have cleared forests and prairies so that the land could be used to grow food and fiber for their growing families. Initially, the transformation of natural ecosystems to the less stable agricultural systems had only local effects on soil quality because there was an abundance of land and relatively few people—only about 1 million people lived on Earth.

While 1000 ha of productive land could support perhaps a single family of humans gathering wild plants and hunting wild animals, the practice of agriculture allowed the same land area to support more than 100 families. As a result, humans survived in greater numbers and by 2000 years ago, their global population had reached some 200 million. Soil productivity began to suffer over wide areas. The salinization of the once very productive irrigated valleys of ancient Mesopotamia in the Middle East (see Section 10.3) and the severe water erosion of the hilly lands farmed by Greeks and Romans (see Figure 17.30) forced these peoples to expand into the less densely populated lands of North Africa and Europe. The rice cultures of Asia had less negative impacts on soil quality as their crop production was centered on riverine floodplains less subject to erosion or salinization, and periodically replenished with new sediments. Human wastes were also extensively recycled to Asian cropland.

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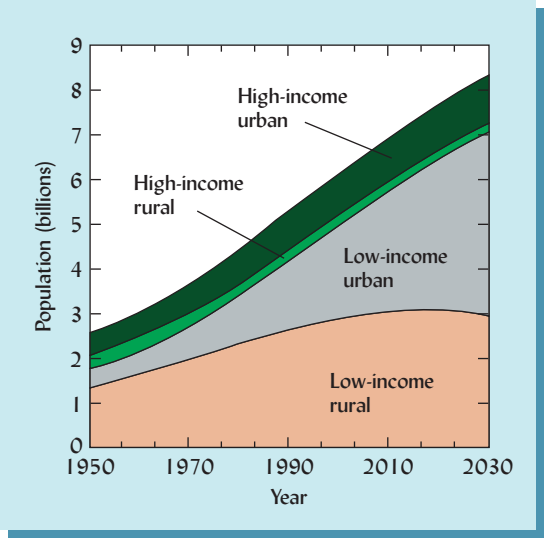

Figure 20.14 *The world's population is expected to rise to about 8.5 billion by the year 2030. Essentially all the population increase will occur in low income countries, most of which are already pressed to provide food for their current populations. Note the rapidly increasing proportion of low income populations that live in urban areas. While considerable quantities of fruits and vegetables are grown in and around cities, most of the staple food required by city dwellers must be produced in often remote, rural areas.* [Graph courtesy of Ray R. Weil based on data from United Nations Secretariat (2007)]

The Population Explosion

As human populations increased, food production kept pace primarily by expanding the area of land cleared for cultivation rather than by increasing the amount of food produced per hectare. One of the greatest expansions of farmland occurred after Europeans "discovered" the Western Hemisphere, on whose virgin soils they soon produced food not only for the new colonies, but for export to the food-deficient parts of the globe. As industrialization began to concentrate growing numbers of people in cities, farmland expansion was required to feed the urbanites. By the year 1800 there were some 1 billion human mouths to feed. By 1940 the number had grown to 2 billion, and by the end of the twentieth century the human population surpassed 6 billion. Thus, while the first billion took some 10,000 years to accrue, the sixth billion took only ten years.

This explosion of the human population during the twentieth and twenty-first centuries has been stimulated largely by the advent of such basic public health measures as purified drinking water, sanitary facilities, and drugs that prevented or controlled many common infectious diseases. Whereas humans had lived in a world in which most of their children died before reaching five years of age, they now found that most of their children survived to have children of their own. The life experiences and child survival changed so rapidly that it often took several generations for people to adapt their reproductive behaviors to the new realities—a process still ongoing in the poorer countries of the world.

The latest projections estimate that the human population will level off at between 9 and 13 billion near the end of this century. Nearly all of the increase will occur in the cities of the world's poorer countries (Figure 20.14). To feed this exploding population, farmers have already had to produce more food in the past half century than had been produced in the previous 10,000 years of the history of agriculture. To achieve this vast increase in food production it was necessary to: (1) **clear and cultivate more land** in the remaining forests (which often occurred on steep, erosion-prone terrain) or natural grasslands (many of which are semiarid, subject to drought and erosion by wind); or (2) **greatly increase the cropping intensity** and the yields per hectare on the more productive lands already under cultivation. Most recent food increases have come (and will continue to come) from enhanced production on existing farmlands. As we shall see, both of these approaches to increasing food production can have serious consequences for the soil quality.

20.6 INTENSIFIED AGRICULTURE—THE GREEN REVOLUTION

When the human population explosion became evident after World War II, many experts predicted widespread starvation, based on the assumption that expansion of cultivated land would be the primary means of increasing food production. They wrongly discounted possibilities for

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increased production intensity on land already in cultivation. Instead of mass starvation, by the 1970s the world actually saw food production increase more rapidly than population. As a result, per-capita food production increased in all major regions with the notable exception of sub-Saharan Africa, where food production rose more slowly than population and the increases were mainly due to bringing more land under cultivation (Figure 20.15). Thus, the threat of massive global starvation was averted, and prices for staple foods like cereals actually fell by as much as 75% in some Asian countries, making food much more affordable for low-income city dwellers in particular.

Component Technologies of the Green Revolution

The increases in food production per hectare of cropland were most spectacular in Asia and Latin America, where the term *green revolution* was coined referring to the new technology. Through a concerted international effort, scientists, governments, and farmers developed and put to use new farming systems that integrated the use of newly created *high-yielding varieties* of cereals (wheat, corn, and rice) with nutrient inputs from *chemical fertilizers* and increased water availability through improved *irrigation*. It should be noted that the green revolution crop varieties were *not* genetically modified organisms (GMOs), as biotechnology capabilities were still decades away. Rather, the new varieties selected by traditional breeding were to be able to take full advantage of high nutrient and water availability in the new systems. The initial efforts mimicked the industrial agricultural models that had come to dominate in the richer countries. Monoculture systems were intensively used and new *synthetic pesticides* were sprayed to keep insects at bay (though insect resistant crop varieties were also soon introduced). In some systems, *multiple cropping* harvested two or even three crops annually from the same piece of land.

Implications for a Healthful Diet

Intensive agricultural systems have focused primarily on wheat, corn, and rice, which collectively provide about half the world's calories and are quite responsive to external inputs, such as water and fertilizers. Therefore, as world food production doubled, fertilizer use and irrigated land area both increased dramatically but the total area of land under crops remained remarkably constant (Figure 20.16).

Unfortunately, less attention has been paid to the pulses (N-fixing grain legumes such as beans, peas, and lentils), fruits, and vegetables. As a result, the area planted to these crops actually decreased in some countries. In addition, the world average yield for pulses has increased only 50% (from 600 to 900 kg/ha) since 1960 while that of the cereals has increased nearly 300%. This has implications for soil quality because integration of vegetables and legumes into farming systems provides for more flexible and diverse rotations and higher plant residue quality for the soil food web.

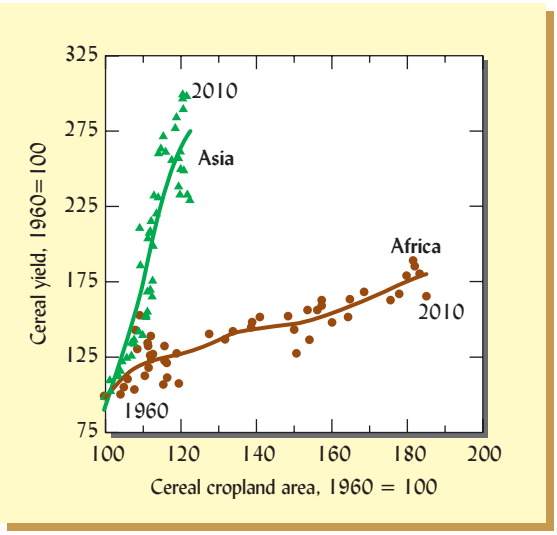

Figure 20.15 *Since the Green Revolution of the 1960–1970s food production increases in Asia outstripped population growth almost entirely because of a 200% increase in yields per unit area of existing cropland. Similar trends occurred in most other parts of the world, except in Africa (south of the Sahara). In Africa food production increased only modestly with a 75% increase in crop yields per unit of land area and an 80% increase in cropland area. The combined effect on food production was not enough to keep up with population growth and the food produced per capita in Africa actually declined.* [Graph courtesy of Ray R. Weil based on data provided by FAO (2014)]

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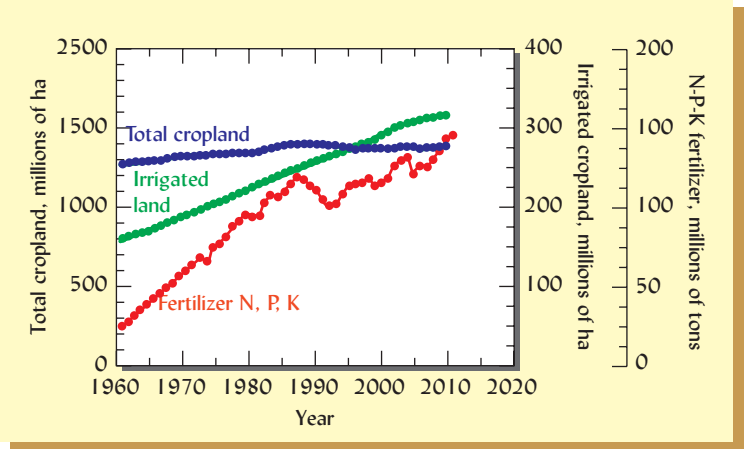

Figure 20.16 *Both fertilizers and water are limited resources and are utilized with both economic and environmental costs. Their use cannot continue to increase forever. However, their impact can continue to increase even though their amounts may not because currently both resources are used quite inefficiently. Irrigated land as a proportion of total cropland increased from 11% in 1960 to almost 30% in 2014. Most of the growth in fertilizer use was for nitrogen, and—for the last two decades—mostly in emerging economies.* [Calculated and graphed by Ray R. Weil from data of FAO (2014)]

There are also implications for human health because, compared to cereals, pulse crops and leafy vegetables are generally higher in proteins and micronutrients, or are richer in certain essential vitamins (although whole cereal grains are important for their B vitamins). Human diseases associated with deficiencies of iron, zinc, copper, and vitamin A are widespread in tropical countries (Section 15.10). Also, the residues from pulse crops provide organic nitrogen for the soil food web and for subsequent crop uptake, allowing reduction in N fertilizer use. Excessive emphasis on cereals has thus reduced several aspects of soil quality and dietary quality in many countries of the world, not just those that underwent the Green Revolution.

Downsides of the Green Revolution Systems

While the Green Revolution technologies certainly saved millions of people from starvation and millions of hectares of forests and grasslands from cultivation, the process was not entirely benign. It was accompanied by traumatic social upheavals as competition from farmers who could afford the new inputs drove from the land others who could not. Landless peasant families often migrated to already overcrowded cities in search of means for survival.

Serious environmental toxicities resulted from poorly controlled, poorly chosen, and overused insecticides. Many insecticides used were highly toxic and all too often accidents and mishandling of these toxins poisoned farmers and their families. In some cases the insecticides actually created more pest problems than they solved because they killed natural enemies (such as predaceous insects and spiders) that had previously kept plant pests in check. The use of herbicides has been associated less closely than insecticides with Green Revolution farming, partly because mechanical cultivation and hand-pulling alternatives have often been less costly where labor is cheap, and partly because wheat and rice are close-growing crops that on their own can often outcompete weeds without much effort by the farmer.

Overuse of ground water for irrigation in some areas has led to depleted aquifers and even contributed to problems with arsenic poisoning (Section 15.9). In some cases, intensively fertilized rice with three crops per year has produced enough crop root and straw residues to increase soil carbon and nitrogen (Figure 20.17). In other cases, though enriched in N, P, and K, heavily fertilized high production soils have tended to become depleted of micronutrients and perhaps more importantly, of organic matter and biological diversity, as monocultures and mineral fertilizers replaced traditional more diverse cropping systems and the use of organic manures and composts. Certainly, landscapes in some of the intensive green revolution producing areas have become less biologically diverse. The traditional patchwork of small fields with many different crops and borders of natural vegetation have been replaced with vast areas planted to one or two varieties of a single crop, grown in larger fields and little or no land left in natural vegetation.

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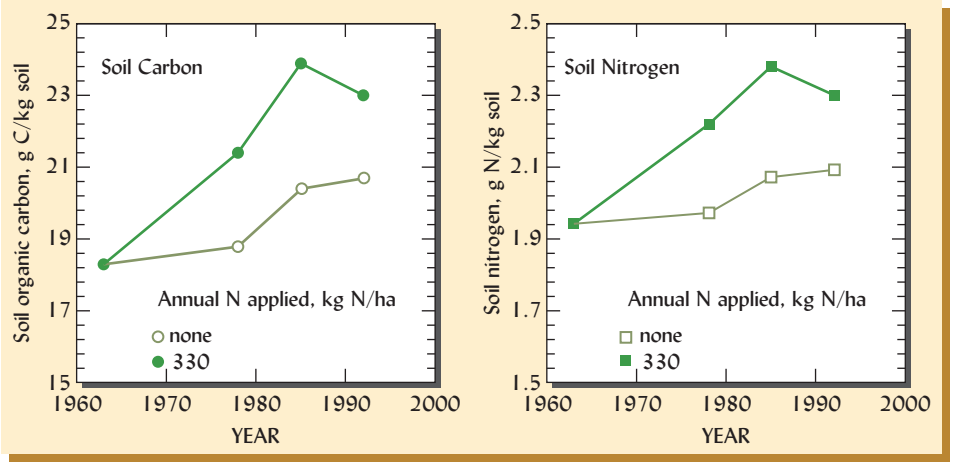

Figure 20.17 *Organic carbon and total nitrogen levels in soil during 29 years of continuous rice cropping with and without nitrogen fertilizer. Three rice crops were grown annually, each receiving 111 kg N ha-1 for a total of 333 kg N ha-1 annually. Organic C and N levels built up more where the rice crops were well-fertilized with N. Phosphorus and potassium were applied to all plots.* [Graphed from data in Cassman et al. (1998)]

Alternative Farming Models to Increase Food Production

Some 40–50% of the Earth's land is used for agriculture, either for crop production or grazing. Moreover, this agricultural land is concentrated in the more potentially productive regions where rainfall is relatively high and periods of freezing temperatures are not too long. The expansion of agriculture is usually seen as being in direct conflict with natural systems that previously occupied the land and provided a range of ecosystems services that typical agricultural fields do not effectively provide. The Nature *versus* Agriculture dilemma is not as completely black and white as it may seem at first. It is also possible to have Nature *in* Agriculture, at least to a considerable degree.

On a landscape scale there are many ways that natural ecosystems can coexist with agroecosystems. In some relatively hilly and varied landscapes, the sites with steep or shallow or poorly drained soils are best left to natural ecosystems which maintain biodiversity and ecosystem functions while crops can efficiently be produced on the sites with more level, deeper, more well drained and fertile soils. Forested riparian zones along streams buffer runoff coming from cropland, shade the water, and provide wildlife habitat and corridors between larger areas of habitat. In some landscapes the riparian zone is too poorly drained or steep for efficient crop production, so the trade-offs are minor. In other landscapes, the cost in productive cropland forgone rises dramatically as the buffer zone thickness increases or the field size decreases. Even within high-yield crop fields, innovative farmers may find room for Nature; for example, with strips of flowering cover crops that provide habitat for pollinators and beneficial insects that enhance the cash crop in a win-win scenario. Many no-till practices leave cropland covered with excellent wildlife habitat in the form of cover crops or crop stubble during the noncropping season. Such space-sharing practices or time-sharing practices offer creative solutions for soil and ecosystem health.

It should be noted that there are also pressures to remove Nature—specifically wildlife—from farming areas. One concern is the damage that wildlife can do in eating the crop. Another, potentially more far-reaching concern in some countries is that wildlife droppings may contaminate produce with bacteria and consumers may be sickened. The latter concern has led to stricter regulation of wildlife on farms that grow produce to be eaten raw. In some cases, fear of legal liability has led to the removal of wildlife habitat from within and around produce farms, diminishing the ecosystem services these areas could provide.

Meeting the Expanding Demand for Food

Population increases will continue to expand world demand for food and fiber, a trend magnified by rising incomes and changing diets in the poorer countries. The first thing poor people tend to buy when their incomes rise is more and better food, in particular, more animal products. Since the production of 1 kg of chicken, pork, or beef requires at least 3, 5, or 8 kg of

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grain equivalent, respectively, these changes in diet magnify the demand for basic foods like cereals. During the coming century the overall food demand is therefore expected to increase by the interactive effects of increasing numbers of people, growing consumption per person, and a larger proportion of animal products in the diets (despite increasing numbers of vegetarians within some rich countries). In addition to this compounded rise in food demand, cropland is also coming under increasing pressure to produce biofuels that will be part of the transition away from fossil fuels.

These realities tell us that whichever models of agriculture we pursue, it will be necessary to ensure that *average* crop yields per hectare in the world keep rising through most of this century to keep up with population growth and avoid potentially massive starvation and destabilization that food shortage would bring. Current rates of yield increase (Figure 20.18) average only about 1.3% per year for the four major crops (corn, wheat, rice, and soybean) that supply nearly 80% of the calories we eat. This rate of increase is *not* enough to meet the 2.4% per year projected growth in demand for food.

Part of the widening gap between increasing yields and increasing demand will likely be bridged by slowing demand as prices rise. A part of the gap is also likely to be bridged by further expansion of agricultural land into land now occupied by relatively undisturbed natural ecosystems. Unfortunately, as we have seen, this method of increased food production results in the loss of biodiversity and important ecosystem services.

Cropland Expansion in the Cerrado South America contains some of the largest remaining land areas in the world where there is still significant potential to expand cultivation, for example, in the woodland-savannah region of central Brazil known as the *Cerrado*. Covering nearly 2 million km^2, the Cerrado has until recent decades escaped much conversion to agriculture because its soils are extremely acid, low in calcium, high in P-fixing capacity, and often aluminum-toxic. The development of high-yielding, aluminum-tolerant varieties of wheat, corn, and soybeans made possible for the first time the production of crops on millions of hectares of level to rolling land in the Cerrado. As a result, the region has become one of the

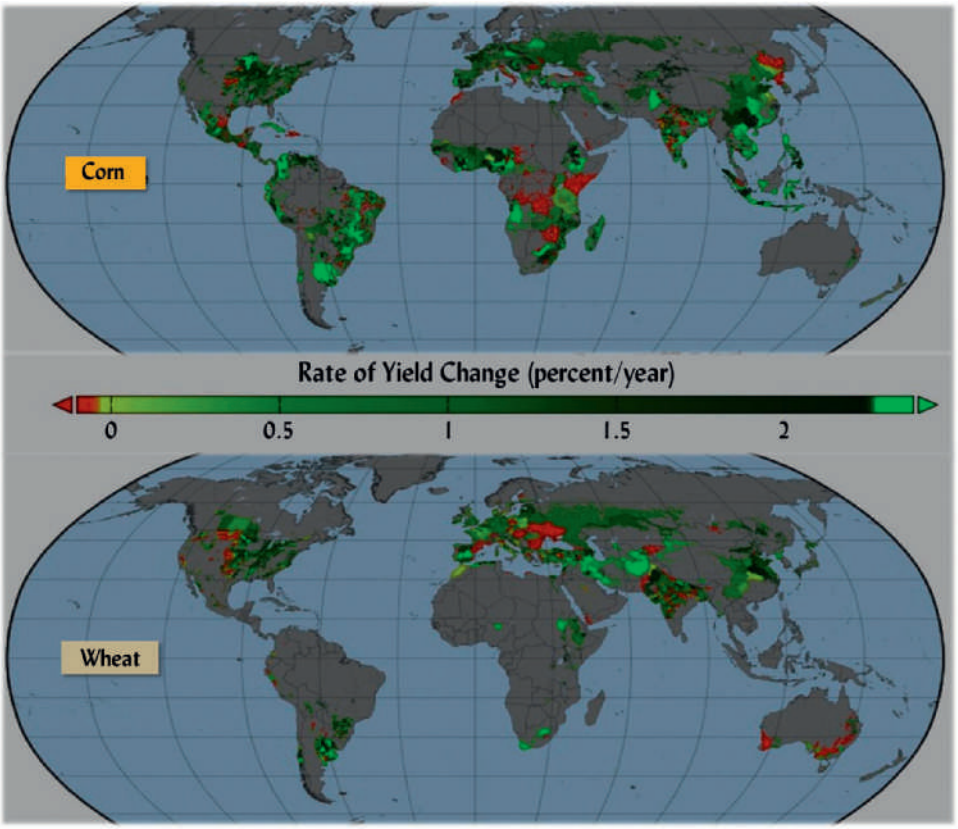

Figure 20.18 *Map of percentage rates of changes in maize and wheat yields based on yield trends from 1989 to 2008 in areas around the world where significant amounts of these crops are grown. Red areas indicate places where yields are declining. Only in the fluorescent green areas are yield increases on track—if sustained—to double production by 2050.* [Modified from Ray et al. (2013)]

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main centers of soybean production in the world. Fortunately, the expansion of farming into this region has taken advantage of no-till and other conservation technologies, so declining soil quality and soil erosion may not be as great a problem as in some earlier major agricultural expansions. However, the trade-off between agricultural expansion and natural biodiversity habitat still applies.

The Cerrado biome is home to many endemic bird species and such large mammals as the maned wolf, jaguar, and giant anteater. With very little (<6%) of their Cerrado habitat under conservation protection, the survival of the wildlife is threatened by the expanding corn, soybean, and ranching operations. If conservation practices are used to protect cropland soils and are combined with diverse landscape uses, development of the Cerrado may be able to produce food and protect the ecosystem.

Closing the Yield Gaps Finally, some of the gap will have to be met by accelerating current rates of yield increase. This acceleration may be a technical and biological challenge for the most highly productive farming regions in rich industrial countries where yields are already very high. In the most advanced farming areas such as the US Corn Belt, yields are thought to be approaching the potential for the soils, climate, and biology. However, the experience of the past few decades shows that with economic incentives, technical innovations such as precision agriculture, improved plant genetics, and advanced nutrient management have pushed crop yields beyond what was once thought possible.

In contrast, in many poor and emerging economy countries, the **yield gap** between what farmers *are now producing* and what the soils and climate suggest they *could potentially produce* is often huge. The difference is commonly seen side by side where resource-poor families farm their plots adjacent to research stations on which inputs and management is carefully optimized. Thus in some of the more climatically favorable regions cereal yields of 10–12 Mg/ha are achieved on research stations, while the average farm produces only 1–2 Mg/ha (in Africa) or 3–4 Mg/ha (in much of South America and Asia). It is evident that large increases in world food production are possible by bringing poor farmers' yields to even half of the potential yields for their environment. Since the current productivity is so far below potential, a doubling or tripling of yields could be made through relatively inexpensive and simple means such as improved seed varieties, conservation tillage, irrigation in some environments, agroforestry, and nutrient inputs in the form of fertilizers, organic resource recycling, and legumes in crop rotations. However, as the locations of several of the red areas in Figure 20.17 remind us (e.g., Zimbabwe and North Korea), yield increases depend not only on changes in climate and biophysical management of soils and crops, but also on a *political and economic* environment that makes sustainable advances possible.

20.7 IMPACTS OF VASTLY INCREASED RATIOS OF PEOPLE TO LAND

The population explosion of the past 75 years has dramatically reduced the amount of land available per person, enormously increasing the intensity of land use—often beyond the bounds of soil resilience. We will discuss briefly the effects on several land-use systems that have suffered major losses in soil quality as a result of these population pressures.

Shifting Cultivation

Indigenous peoples and their ancestors around the world have developed traditional pastoral and crop-production systems that take advantage of soil resilience. These systems rely on the ability of soils under natural vegetation to recover from the temporary degradation caused by losses of nutrients, soil organic matter, and soil structure during brief periods of agricultural use. One of these indigenous systems is a type of shifting cultivation, which has been practiced for generations in tropical forests around the world. It involves the slashing of native vegetation to make small clearings in the forest and then burning the cut material (Figure 20.19) to prepare the land for producing food crops for a few years. Hence the system is sometimes termed "slash-and-burn" agriculture. Crops are grown for only a few years until the supply of nutrients from the ashes and soil organic matter is depleted, or until weeds become

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Figure 20.19 *Shifting cultivation. (*Left*) Slash and burn scene in the Amazon rain forest in Bolivia in which two fields have been recently slashed and burned, while several other fields have been abandoned and are in various stages of forest regrowth. (*Right*) Another field that has been slashed and burned in Sri Lanka. Most of the N and S are lost in the smoke, but the other plant nutrients become concentrated in the ashes. There are no weeds at this point, but in a few years, weed infestation and soil fertility depletion will force the cultivator to move on to another site.* (Left photo courtesy of Rhett A. Butler, mongabay.com; right photo courtesy of Ray R. Weil)

intolerable. The farmer then moves on to slash and burn another small plot, cultivates it for a few years, and then abandons it, too. This process is repeated, shifting from one site to another, until after some 15–20 years, the initial site is once again cleared of the now semimature natural vegetation, and the process is started over. During the 15–20 years of forest regrowth, the natural vegetation at least partially rejuvenates the quality of the soil by adding organic residues, recycling nutrients from deep in the profile, and fixing nitrogen from the air.

During the past century the number of people dependent on shifting cultivation has increased dramatically. More than 300 million people, most of them desperately poor, practice some form of shifting cultivation on enormous land areas, primarily in the tropics and subtropics. Their activities account for a major part of tropical deforestation. Once quite sustainable, the shifting cultivation system now fosters soil and environmental degradation and is nearing collapse in many regions. The reason is simple math—the amount of land needed per person for sustainable shifting cultivation is very large. Attempts to practice shifting cultivation with less land per person undercut the ability of the system to sustain soil quality.

For example, consider a farmer using shifting cultivation who can produce enough food for his family by cultivating 1 ha of land. In the sustainable traditional system, this farmer might cultivate the 1 ha for three years and then abandon it to forest regrowth for 15 years so that 18 years elapse between repeated clearings of a given plot of land. This means that 6 ha of land (18 yr/(1 ha $\times$ 3 yr)) are required to produce the needed food—1 under cultivation plus 5 under some stage of natural vegetation fallow for recovery. As the human population in an area doubled and quadrupled during the past half century, the amount of land available per person was halved and quartered. Shifting cultivators either had to slash new, virgin forest (a difficult task and usually not an available option) or they had to reduce the number of years between abandoning a plot and returning to it. As fallow periods declined from nearly 15–20 down to only 3–5 years, the time was insufficient for regenerative processes to replenish soil nutrient and organic matter levels and to constrain soil erosion (Figure 20.20). As a consequence, soil quality has deteriorated, along with yields of food crops and family wellbeing in most areas where shifting cultivation is practiced.

Slash-and-burn systems also adversely affect the atmosphere. The CO_2 and other greenhouse gases released in the burning process are thought to make a significant contribution to total global warming. To prevent worsening of soil quality and climate change, cultivators in these areas need viable alternatives to the intensified shifting-cultivation systems that the circumstances just described now force them to use.

Nomadic Pastoral Systems

Nomadic pastoral systems on common lands in arid to semiarid areas, combined with increased human populations and extended periods of drought, have adversely affected soil quality, especially in the Sahel region of Africa and the semiarid regions of western China. Much as in the case of shifting cultivation just described, when the numbers of nomads and their livestock were low, the rangeland had very long periods to recover between very brief visits of the grazing herds

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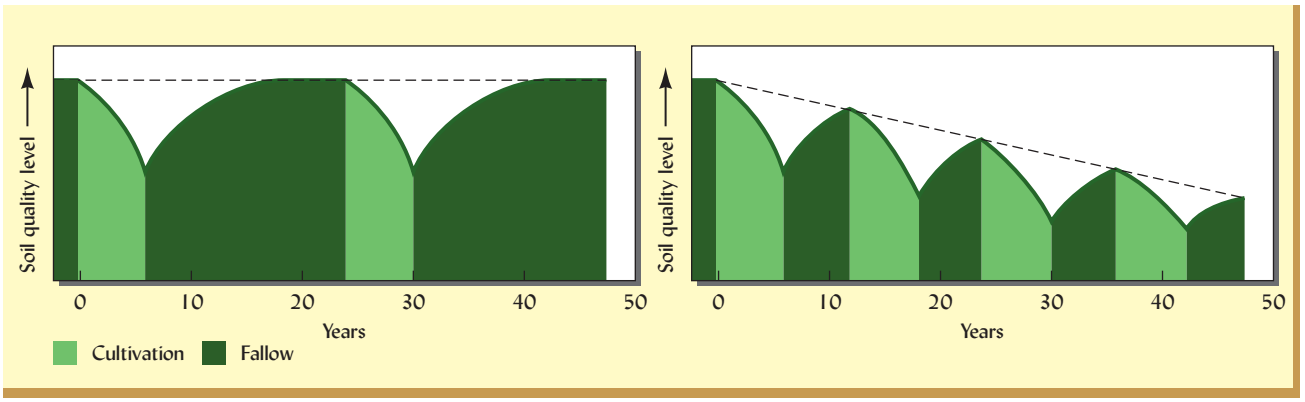

Figure 20.20 *Changes in soil quality under two shifting-cultivation systems.* (Left) *In the system with a long fallow period, the natural vegetation is able to help regenerate the level of fertility and soil quality after cropping.* (Right) *With a shorter fallow period so common in areas of high population pressure, insufficient regeneration time is available, and the soil quality level declines rapidly. These figures also illustrate the concept of soil resilience.* (Diagram courtesy of N. C. Brady)

(Figure 20.21). The recovery period between brief grazing episodes required for sustainability varies inversely with rainfall, from one month in some humid regions to 6–24 months in much drier regions. Increased animal numbers, or even constant numbers with less forage to consume because of drought, result in longer grazing events and little or no plant recovery between grazing episodes—in a word, *overgrazing*. The more nutritious grasses are mostly eliminated, and only less-palatable shrubs remain. Overall plant production is reduced, less plant residue is returned to the soil, and soil organic matter is not replenished. Wind erosion increases (see Section 17.11), and overall biological productivity declines, along with soil quality. Nearly 100 million people now live in areas where such effects are occurring.

Marginal and Degraded Lands

Human population pressures have also resulted in expansion of cultivation into areas that are marginal for agriculture, such as erosion-prone, steep hillsides or semi-arid lands with fragile vegetative cover and unreliable rainfall. Many families, commonly landless, in Central and South America, Africa, and Asia are forced to use these areas to survive (Figure 20.22). Including farm families that practice shifting cultivation, some 800 million people produce their food on forested hillsides.

Figure 20.21 *Herds of sheep and cattle push a semiarid soil beyond its resilience limits by staying too long and returning too soon to each piece of land.* (Photo courtesy of Ray R. Weil)

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Figure 20.22 *Desperately poor families carve out farm fields from the forest on steep Central American hillsides. Even with rudimentary contour ridges and grass barriers as seen in the foreground field, rates of soil erosion and nutrient loss can be disastrous.* (Photo courtesy of Ray R. Weil)

The marginal croplands generally exhibit little resistance to degradation and poor resilience once they are abandoned. Removal of perennial vegetative cover, depletion of plant nutrients in the crop harvests, and structural deterioration with tillage all lead to rapidly declining biological productivity, diminished soil quality, and increasing susceptibility to soil erosion by water or wind.

During the past half century people have degraded some 2 billion ha of land (see Figure 17.1). Unfortunately, there is little agreement on how much land has been degraded or where the degraded land is located. Knowledge about the distribution and condition of degraded lands is needed because some development specialists and governments have suggested that any agriculture expansion should be directed onto degraded lands where ecosystems are already compromised rather than destroy more pristine forests and savannahs. On the other hand, studies have shown that biodiversity is often actually higher in lower productivity, less agriculturally favorable landscapes. Therefore it may make more sense to convert only the most productive sites from natural systems to agricultural since food production needs could be met with less total land being converted.

Studies using satellite sensing of vegetation give a very different picture of degraded lands than surveys using soil properties and expert opinion based on field experience. Estimates of the extent of the world's seriously degraded land range from 1 billion ha to over 6 billion ha (10–60% of the world's land area). Data in Table 20.6 suggest that by 1990 (the latest figures of this kind available) soil quality had declined on 38% of the world's agricultural land, on 21% of permanent pastures, and on 18% of forests and woodlands. Soil degradation on agricultural lands has been most drastic in Africa and Central America, but the problem extends to all continents. On about half of the land suffering soil degradation, erosion by water is the main cause, with another quarter of the area suffering from erosion by wind. Also widespread is degradation due to compaction, salinization, and depletion of nutrients. In more limited areas (but still tens of millions of ha worldwide) soils have suffered acidification, pollution, and waterlogging. Since rising demands for food, fiber, biomass, and living space are sure to continue to increase pressure on soil quality, we now need to join in aggressive efforts aimed at reversing the degradation trends.

Urbanization and Sprawl

The increased use of land for urban, industrial, and transportation purposes also has its impacts on soil quality. The problem of urban sprawl has resulted in losses of cropland, pasture, and

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Table 20.6
LAND AREAS IN AGRICULTURE, PERMANENT PASTURE, OR FOREST AND THE PERCENTAGES OF EACH SUFFERING DEGRADATION AS A RESULT OF HUMAN ACTIVITIES. MILLIONS OF HA
Reductions in soil quality are most severe in agricultural lands, particularly in Africa and Central America, where more than two-thirds of the cultivated lands are adversely affected.

Land use	Africa	Asia	South America	Central America	North America	Europe	Oceania	World
Agricultural land								
Area	187	536	142	38	236	287	49	1475
Percentage degraded	**65**	**38**	**45**	**74**	**26**	**25**	**16**	**38**
Permanent pasture								
Area	793	978	478	94	274	156	439	3212
Percentage degraded	**31**	**20**	**14**	**11**	**11**	**35**	**19**	**21**
Forest and woodlands								
Area	683	1273	896	66	621	353	156	4048
Percentage degraded	**19**	**27**	**13**	**38**	**1**	**26**	**8**	**18**
All lands								
Area	1663	2787	1516	198	1131	796	644	8735
Percentage degraded	**30**	**27**	**16**	**32**	**8**	**27**	**16**	**23**

Reorganized and calculated from Oldeman et al. (1990).

forest lands around the world (Figure 20.23), especially in the developing countries, where population pressures are greatest and economic growth is most pronounced. Global urbanization alone is thought to claim well over 1 million ha annually. Furthermore, this land is usually prime land for plant productivity, since many growing cities were originally located to take advantage of good cropland nearby.

The world's land area taken up by urban uses has been estimated in various ways, depending on the definition of "urban land" that applies. Most broadly, some 3% of the world's land (excluding Antarctica and Greenland) is urban land as defined by administrative political boundaries. Typically, more than half the land within official city boundaries is not actually built up. The best estimate (from 2010) of the extent of land actually built up in urban uses is about 0.65% of the world's land. Finally, about 0.45% of the world's land is urban by the narrowest definition that considers only land covered by impervious surfaces (i.e., asphalt, concrete, rooftops).

Figure 20.23 *Urban sprawl can devastate soils that once provided food, fiber, and other ecosystem services.* (Left) *Poor people haphazardly expand Tegucigalpa (Honduras) onto steep, erodible forest lands.* (Right) *Wealthy people haphazardly expand Phoenix (Arizona, USA) onto highly productive irrigated farmland. The soils will likely never again be available for forestry or agricultural. Their new soil quality function will involve foundations for roads and buildings, and environments for lawns and gardens. If the soils are protected from erosion (too late for the scene at left), soil quality for these new functions may well be quite satisfactory.* (Photos courtesy of Ray R. Weil)

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20.8 SUSTAINABLE AGRICULTURE IN DEVELOPED COUNTRIES

A twofold challenge lies ahead: (1) to satisfy the enormous and growing needs of society for food, fiber, and biomass produced using soils, while (2) maintaining or even enhancing the quality of the soil resource and the larger environment. To meet this challenge, a new paradigm of global agriculture is beginning to unfold.

New Paradigms of Plant Production

In the past, the limits of *technology* and *short-term economic profitability* have been the primary driving forces shaping food-production systems. While these considerations must still be accommodated, there is a growing recognition that we must give greater emphasis to an *ecological basis* for our agricultural systems. This new sense of direction will use science and technology to understand how agroecosystems interact with other ecosystems. It will help us focus on establishing food-production systems that minimize resource losses and maximize the stewardship of natural resources for food production, for natural habitats, and for the other ecosystem services and soil quality goals discussed earlier in this chapter. We will start with some significant changes needed in intensified commercial agricultural systems.

Food and fiber production on prime agricultural lands will continue to be highly intensified, in terms of high yields and continuous cropping, but not necessarily in terms of chemical inputs or tillage. To sustain this intense production, we must employ new soil and crop management systems that will *reduce pollution* of soil, water, and the atmosphere, decrease *soil erosion*, increase the *efficiency of nutrient and water use*, maintain or increase the *quantity and quality of soil organic matter*, and increase *biological diversity*.

Perennial Grains

One of the most far-sighted efforts to develop a new, more sustainable yet highly productive agriculture is being built around the concept of mimicking Nature's prairie ecosystem. Inspired by a small group of visionaries who established The Land Institute in Salina in Kansas, USA, in the 1970s, a global network of scientists is now working to develop a system of perennial grain crops. The idea is that, like the prairie grasses and forbs, these plants will produce enormous deep root systems that build healthy productive soils. But unlike most prairie plants, these perennials will also produce edible and harvestable seeds from which people could make their bread. The vision is a restored prairie that eliminates the need for annually disturbing the soil to plant crops. Grown, like the prairie, in mixed stands of grasses, legumes and composites, these systems will aim to produce an annual harvest of nutritious seeds, while providing ecosystem services rivaling those of the native prairie (Figure 20.24). Although still a rather distant goal, measureable progress has been made in breeding the grain-bearing perennials that may one day make up these future prairie farms.

In the meantime, other innovative scientists and farmers are developing promising new ways to grow traditional food crops in much more sustainable systems than have been the norm for the past half century. Since maintenance of soil cover and improved nutrient cycling are at the heart of these efforts, we will discuss them first.

Keeping the Soil Covered and Rooted

Perhaps the most important requirement for maintaining and improving soil health in intensive agriculture is to keep the soil surface covered with growing plants, residues, or mulches, and the profile permeated with live roots at all times. Proper cover can greatly reduce soil loss by erosion (Section 17.5) and water loss by runoff and surface evaporation (Section 6.4). A diverse and generous supply of plant residues on the soil surface also stimulates the soil food web organisms (Chapter 11), enhances aggregate stability (Sections 4.5 and 4.6), increases the infiltration of rain and irrigation water (Section 5.6), and increases both soil organic matter and biodiversity. Living root contribute to many of these same functions plus create biopores, cycle nutrients, and support the soil food web. In short, keeping the soil covered and rooted is one of the best paths to improved soil health (see also Section 20.4).

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Figure 20.24 *A diverse experimental prairie ecosystem at The Land Institute in Salina in Kansas, USA. It is comprised of native perennial plants specially bred through selection to bear large, cereal-like seeds (inset). Such perennial grains would not need to be planted every year and would function much like the native prairie, but supply harvestable seeds meant to supplant the culture of annual cereal grains like wheat in providing food for people. Modeled on the natural prairie, the perennial grains would ideally be self-sustaining and build soil health through the contributions of large perennial root systems.* (Photos courtesy of Ray R. Weil)

Conservation tillage, including no-till, not only ensures organic residue coverage on most soils, but costs less in terms of both money and energy inputs than do most tilled systems. Combining conservation tillage with cover crops or green manures provides synergistic benefits to soil health and environmental protection (see Sections 16.2 and 17.6) in all but perhaps the very driest climates.

Biomass for Biofuel Production[4]

An emerging challenge for the soil resource is the new and growing demand for plant biomass, produced not for food or fiber, but as a renewable feedstock to replace nonrenewable petroleum for the energy industry. Projections suggest that soil resources may be increasingly devoted to energy crops as the United States and other countries attempt to shift their energy sectors away from reliance on nonrenewable and greenhouse gas-generating fossil fuels. In particular, dramatic future growth is projected for the production of biofuels from plant biomass (Figure 20.25, *center*). Nearly all the ethanol production shown in the graph in Figure 20.25 was made from corn grain, and therefore competed with human food uses (direct or indirect via livestock) of corn. Advances are being made in fermentation processes, so that ethanol may be made increasingly from cellulose-based materials such as crop residues and leafy tissues, which would remove the biofuel from direct competition with food uses.

Many questions remain as to the energetic and ecological efficiency of biofuels, even with cellulosic fermentation. If only the burning of the fuel itself is considered, biofuels may serve as a carbon-neutral energy source. That is, the CO_2 emitted in burning the biofuel is balanced by the CO_2 just recently removed in growing the biomass. However, most studies show that large amounts of fossil fuel energy must be used to grow the biomass and run the biofuel refineries. In fact, the energy input into the biofuels industry may nearly equal—or even exceed—the energy output in the form of usable biofuels (Figure 20.25, *right*). Therefore, even with technological advances, growth in the biofuels industry is—and will probably remain—quite dependent on large government subsidies and policies that mandate biofuel use.

The environmental, as well as economic, sustainability of biofuels must be carefully considered. Engineers and system designers have suggested plans to harvest as much fermentable

[4]For an example of biofuels production planning that appears to ignore soil quality, see Ragauskas et al. (2006) and for rebuttals recognizing the soils and sustainability aspects, see letters edited by Kavanagh (2006).

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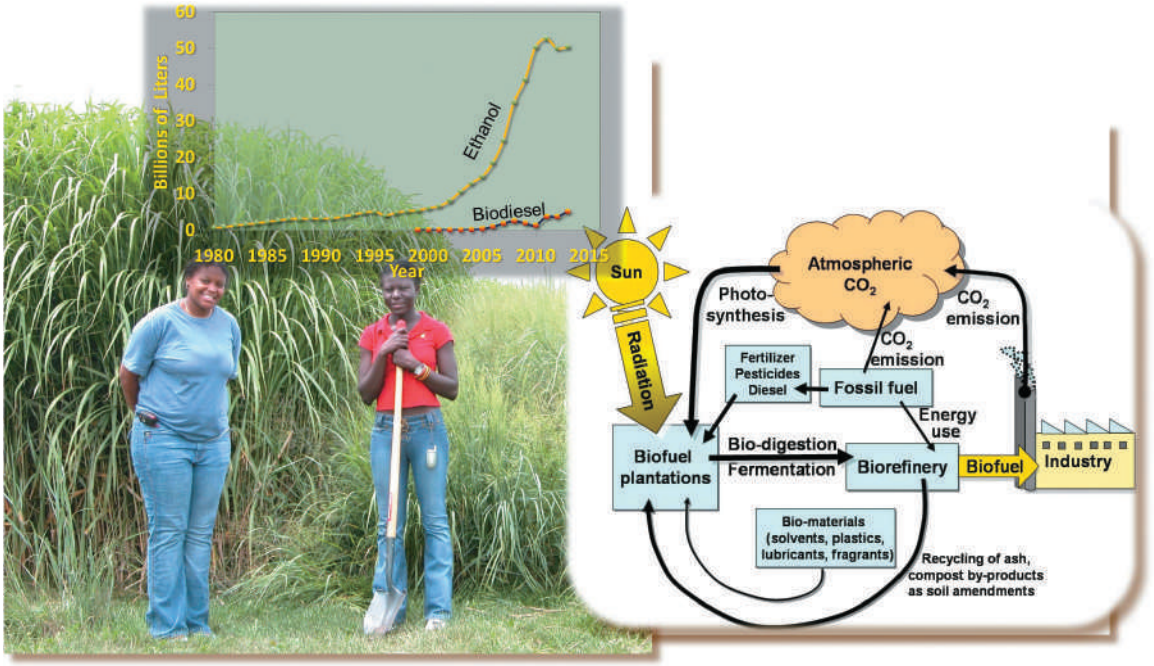

Figure 20.25 *Soil resources are used to grow plant biomass for production of such biofuels as ethanol and biodiesel. Research assistants stand in front of two grass species* (left) *being studied as sources of biomass for cellulosic fermentation to ethanol. The taller species is* Miscanthus giganteus *and the shorter is* Panicum virgatum *(Switchgrass). Burning biofuels may be carbon-neutral, but much of the energy value of the biofuels produced is offset by the fossil fuel energy inputs used to grow the plants and run the biorefineries* (right)*. The fossil fuel inputs for the biofuel plantations are mainly in the form of nitrogen fertilizer, pesticides, and tractor fuel, the use of which can be minimized by ecological farming practices. Production of biofuels in the United States (graph) increased exponentially between 2005 and 2010 and their contribution to transportation energy use in the United States rose to about 20% of the total. Biofuel production can be sustainable only if adequate biomass is left in the field to maintain soil quality.* [Diagram courtesy of Ray R. Weil based on concepts in Lal (2006); data from USDA/Economic Research Service; photo courtesy of Ray R. Weil]

biomass as possible from each ha of land. They have even called for plant breeders to create plant varieties that funnel larger amounts of energy to harvestable shoot biomass and devote less to root production. These suggestions run counter to the requirements of soil quality. It is essential, therefore, that soil scientists become vocal in reminding planners that biofuel production can be sustainable only if the crops are sustainably produced. It is also essential that an adequate portion of the biomass is left as surface residue in the field to protect against erosion and maintain soil quality (see Table 12.6). This is one reason why perennial grasses (e.g., *Miscanthus* and switchgrass, Figure 20.25, *left*)—especially mixed species stands—may be a more sustainable option than corn residues as a biofuel feedstock. Such grasses present several advantages over corn grown for this purpose, including: (1) a dense root system that should protect soil quality and very effectively utilize soil nitrogen and (2) a dense perennial growth habit that may preclude the need for herbicides.

Nutrient Management

Nutrient management that applies the principles outlined in Chapter 16 will continue to be essential for maintenance and improvement of soil health and protection of the environment. Using the soil food web and chemical buffering processes to supply the right balance and amounts of nutrients for optimal plant growth and quality remains the central focus. Such management must significantly reduce the rates of nutrient application in parts of Europe, the United States, and Asia where nutrient additions currently far exceed plant uptake. In other areas, such as sub-Saharan Africa, additional nutrients will need to be supplied. Increasing attention will have to be paid to micronutrients in some regions. In all regions, greater attention needs to be given to improving the efficiency of nutrient use, and to more effective recycling of all nutrients in the agroecosystem.

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Combining Organic and Inorganic Sources

Research has repeatedly shown that combining inorganic fertilizers with organic nutrient sources (e.g., manure or crop residues) can maintain, or even increase, yields and at the same time improve soil quality and health. This is due in part to enhanced nutrient cycling and to the influence of diversified crop residues on both the quality of soil organic matter and health of the microbial community. Figure 20.26 provides some insights into how the combination of organic and inorganic nutrient sources can employ the microbial biomass to enhance nutrient availability and plant growth.

In conventional systems with only one or two crops in the rotation, the level of the *active pool* of soil organic matter is usually low. In more diversified systems with several different crops in the rotation, and with somewhat lower rates of fertilizer, much higher levels of the active organic matter fraction have been found. The soil in such high diversity crop systems usually also has higher levels of microbial biomass N and higher rates of N mineralization. The interaction among the diversity of crops being grown, the quality of soil organic matter, and the microbial numbers and their ability to release nitrogen and other nutrients for plant uptake are illustrated in Table 20.7.

Crop Rotations

Crop rotations provide numerous advantages over the monoculture systems often favored in intensified agriculture. Yields of two crops are higher if they alternate with each other on a given field, or if they are grown together simultaneously as an *intercrop*. If legumes are included in the rotation, they provide additional nitrogen to the system, and improve soil quality by enhancing the incorporation of crop residues into soil organic matter (Figure 20.27).

Forage crops encourage animal production on a sustainable, decentralized basis and assure the availability of animal manures that supply nutrients and long-lasting organic matter benefits. Close-growing crops in the rotation also help control soil erosion, and, with the help of crop residues, markedly increase the soil's water-infiltration capacity. There are few practices that can boost soil health as well as establish a mixed grass-legume pasture and graze it with livestock for several years (Figure 20.28).

Even growers of such high-value crops as vegetables and ornamentals are beginning to see that they can profit more and benefit from healthier more resilience soils if they practice crop rotations that use one-third or less of their land for the high-value (usually soil-depleting) crops while growing lower-value but better soil-building crops (such as pasture, hay, or small grains) on the remaining land. If fall or winter cover crops are included (Section 16.2), end-of-season nutrients left by the main crop can be saved, water contamination can be averted, and additional residues are added to the soil. Cropping system studies have clearly established that rotations involving close-growing crops, including legumes, are a reliable path to improved soil health, especially where water is severely limiting.

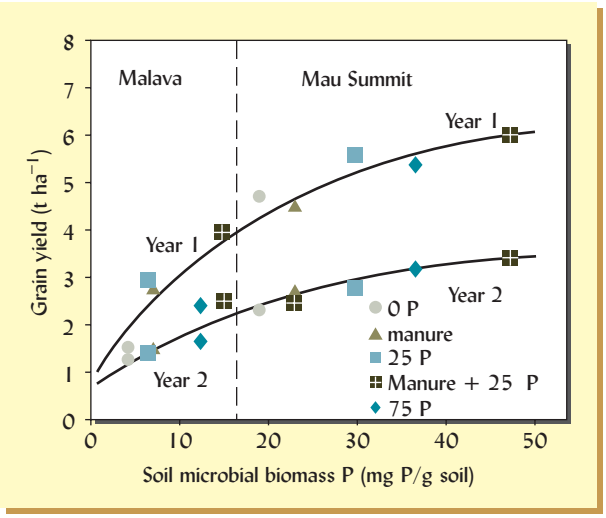

Figure 20.26 *The relationship between soil microbial biomass P and corn grain yield in response to inorganic and organic fertilization and the combination of the two. The soil amendments tested were (●) a no P added control, (▲) 1.9 Mg/ha of local cattle manure (containing 5 kg P/ha), (■) 25 kg/ha of commercial fertilizer P, (⊞) the combination of manure + 25 kg/ha fertilizer P, and (♦) 75 kg/ha of fertilizer P. The latter amendment was meant to partially saturate the soil P-fixing sites and provide P for several years of cropping. The combination amendment (⊞) was designed to the fertilizer P to cycle via the microbial biomass into organic forms, and thereby avoid fixation on the colloid surfaces. The experiment was repeated at villages in Kenya. At Malava the soils were acid (pH 4.5) sandy clay Kandiudults with a high P-fixing capacity. At Mau Summit the soils were more fertile, less acid (pH 5.5) silty clay Melanudands with lower P-fixing capacity. The treatments were applied in years 1 and 2 and corn was grown each year for grain. All plots also received 100 kg inorganic N/ha. Note the close relationship of grain yield to soil microbial biomass P across both sites. The generally higher yields in year 1 were due to better rainfall that year.* [From Ayaga et al. (2006)]

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Table 20.7
CONSERVATION PRACTICES INFLUENCE SOIL QUALITY FACTORS RELATED TO ORGANIC MATTER
In each region, soil was analyzed from six pairs of adjacent fields, one on which conservation practices (reduced tillage, greater crop diversity, more sod crops in rotation, and/or use of organic nutrient sources) were used, while conventional practices (more tillage, less diversity, etc.) were used on the other.

	Coastal plain soils		Piedmont soils	
Properties	Conservation management	Conventional management	Conservation management	Conventional management
Total organic C, g/kg	12.5	8.3	19.6	15.5
Active organic C,[a] mg/kg	121	75	134	112
Microbial biomass C, % of total organic	2.4	1.3	2.6	2.3
Nitrogen mineralization rate constant[b]	38	33	42	36
Aggregate stability, %	73	58	74	66
Specific maintenance respiration[c] (qCO_2), mg CO_2 g microbial biomass C^{-1} day^{-1}	41	72	18	32

[a]Mainly sugars extracted from soils after disruption with microwaves.
[b]The rate constant k, day^{-1}, in the first-order decay equation $N_p = N_o e^{kt}$.
[c]Higher numbers indicate ecosystem stress and more energy expended just to survive.
Data from Islam and Weil (2000).

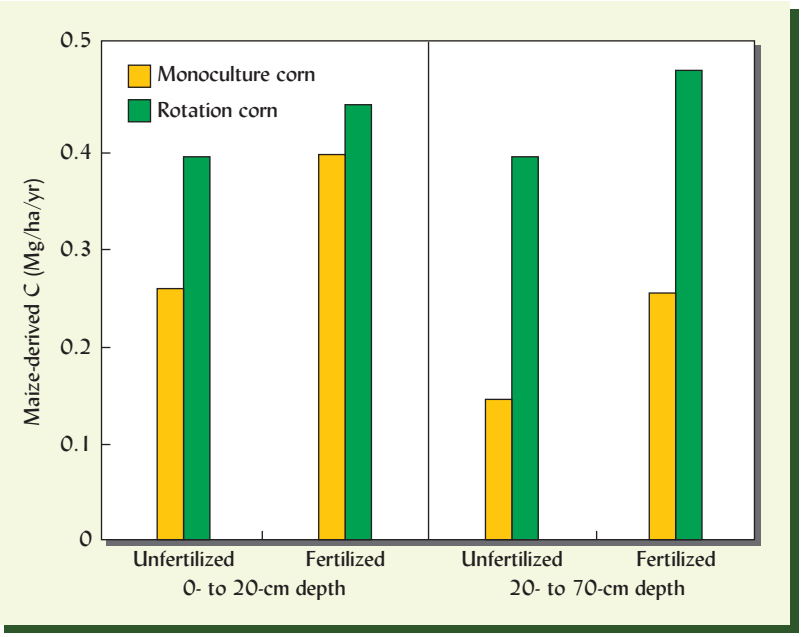

Figure 20.27 *Growing corn in a legume-based rotation rather than in monoculture enhanced soil quality as evidenced by the amount of soil carbon that was derived from the corn residues. The benefit of using a rotation was especially evident in the subsoil (20–70 cm deep). These data are from a long-term (35-year) experiment in Ontario, Canada, on a Humaquept (Humic Gleysol, Canadian system).* [Drawn from data in Gregorich et al. (2001)]

Water Management

Scarcity of water is likely to challenge our ability to meet future food demand. Greater efficiency in using both precipitation and irrigation water must be achieved. Diversified crop rotations that include close-growing crops, along with conservation tillage or no-till, can provide greater soil cover, increased water penetration, and decreased water runoff and soil erosion. This leads to more efficient water use for plant productivity. Likewise, such irrigation management systems as drip irrigation that reduce the quantity of water needed to produce plants will

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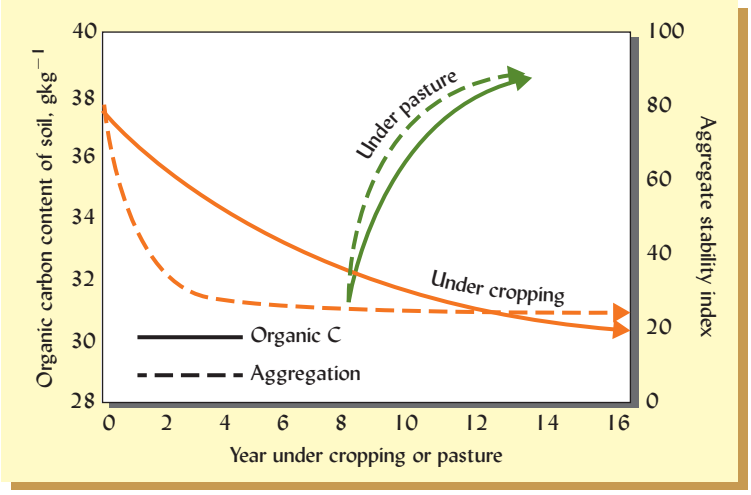

Figure 20.28 *The Mollisols of the southeastern Pampas region of Argentina are inherently productive and high in soil organic carbon. However, experience has shown these soils to have low resistance to degradation when cropped. On the other hand, researchers found that these soils were very resilient; including several years of perennial pasture in the rotation after 7–8 years of grain crops could rapidly restore high levels of both soil organic carbon and aggregate stability in the upper 20 cm of soil.* [Modified from Wingeyer et al. (2015)]

have to be more widely used. Improved drainage systems serving irrigated areas must reduce the buildup of salts, thereby maintaining the quality of the soil (Sections 10.7–10.9).

Biological Diversity

Intensified cropping systems that involve a diversity of plant species in the rotation as cash crop or cover crops, especially if both legumes and nonlegumes are included, have been shown to increase the biological activity and diversity in soils. Not only will there be more microorganisms, but the diversity of organic food for them will encourage greater microbial diversity. Likewise, the cycling of nutrients among organic and inorganic forms requires a diversity of soil organisms. Such diversity will enhance essential physical, chemical, and biological processes on which soil quality depends.

Effects of Insecticides. Chemical insecticides that are commonly used in intensified agriculture systems can adversely affect soil quality. While some organic chemicals adversely affect a broad spectrum of soil organisms, others are selective, reducing biological diversity more than overall abundance (Sections 11.12 and 18.4). Some soils treated a century ago with high levels of arsenic- or copper-containing insecticides still contain toxic levels of these chemicals. The use of insecticides, especially those with residual action or high mobility in the soil, can decrease soil quality with regard to the environmental protection and biodiversity roles of soils. Because of the uncertain effects of today's insecticides on soil quality, integrated pest management (IPM) systems that minimize the use of pesticides, or organic farming methods (see Section 20.8) that eliminate the use of synthetic pesticides, should be emphasized.

Effects of Herbicides. Herbicides are chemicals that are meant to kill plants—presumably the unwanted plants that we call weeds. Herbicides are very widely used in intensive production of row crops where the wide spacing between crop plants gives weeds an early opening to compete. Different herbicidal chemicals vary widely with regard to their mobility, persistence, and toxicity to soil organisms (and people). Those that are long lasting and relatively mobile in soils have created major water pollution problems (Section 18.3). Others that are immobile and show no soil activity have played a very positive role in enhancing soil quality by facilitating conservation tillage (Section 17.6). To maximize soil quality, herbicides should be used selectively and with restraint. Research shows that low to moderate weed populations can often be tolerated without sacrificing crop yields. Furthermore, the intensive use of herbicides to strictly enforce a single species monoculture negatively impacts soil quality because the lack of plant biodiversity can lead to reduced diversity and resilience of the above- and belowground communities associated with the shoots and roots of these plants.

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Urban Farming

As mentioned in Section 20.6, much of the land in areas classified as urban use, such as land within city boundaries, actually is not covered with concrete or other impermeable surface, but has exposed soil and may support vegetation (Figure 20.29). The ratio of impermeable surface to total urban land varies quite a bit, especially among countries, with those in Europe and Asia generally having more densely built-up cities than the United States or Australia. In any event, most cities have many areas of parks, rights of way, dwelling yards, vacant lots, and the like where soils are exposed and sunlight and rain water reaches. Rooftops are especially well placed for sun and rain exposure, but of course provision must be made to supply some kind of soil or growth medium.

As potential sites for growing food, many urban venues have special challenges. Toxic levels of lead, zinc, cadmium, and organic contaminants are a concern in the soil (and wind carried dust) of vacant lots and roadside rights of way. Some urban community gardens may help solve one kind of food security problems only to fall prey to another (securing the vegetable from being harvested by uninvited strangers). Roof top gardens pose perhaps the most challenges, with environmental extremes and usually a need for a very shallow layer of a low bulk density growth medium to avoid collapsing the building. Biochar may offer some potential to meet these growth media requirements as adding large amounts (5–10% by weight) of biochar to soils, not only reduces the mass density, but also increases water retention and decreases loss of nitrogen, phosphorus, and organic carbon.

Finally, in some recently developed "vertical farming" schemes, the building *is* the farm. In vertical farming, food is produced in multistory greenhouses fitted with highly automated and climate-controlled hydroponic (soil-less liquid media) systems. This concept basically contradicts all the principles of ecological food production. In multistory greenhouses, except for the top layer, plants will have to be provided with artificial light. So agriculture in this form is no longer the great solar energy harvesting system—but instead becomes a power user, even if the most energy-efficient LED bulbs are used. These high-technology urban farms will be limited to certain plants that are amenable to hydroponic production, with gourmet lettuce the most likely crop. Compared to outdoor farming in natural soil, well designed and managed vertical farms can be expected to produce much higher yields per square meter of space, but at much higher cost, as well.

All of these urban farming alternatives can help improve the availability of fresh vegetables in urban dwellers' diets. Intentional, well-managed use of exposed urban surfaces can also help cities cope with storm water runoff and nutrient pollution (see Section 6.2). However, despite some claims to the contrary, urban farming cannot supply a significant part of

Figure 20.29 *Food production—especially vegetable production—can take place in areas designated as urban land use. Backyards and front yards (a), roof tops (b), traffic islands (c), vacant lots (d), and community garden plots (e) are some of the urban venues where food can be grown.* (Photos courtesy of Ray R. Weil)

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the staple crops that provide most of the calories and protein (e.g., the wheat for bread or the corn that poultry turn into eggs) needed in the diets of the millions of humans in the cities. Therefore, urban farming cannot significantly impact the global land–food conundrum discussed earlier in this chapter.

20.9 BIOCHAR: HYPE OR HOPE FOR SOIL QUALITY?[5]

In Chapter 12 (Box 12.2) we discussed the chemistry of naturally occurring black carbon and its important role as a component of stable soil organic matter. Biochar is a similar black carbon substance, one purposefully made as a soil amendment. Biochar was used by humans to improve soils thousands of years ago (see Box 20.4), but biochar has become a topic of intense interest in recent years because it has been suggested as potential tool to ameliorate climate change by sequestering carbon in soils, and because its use has been reported to exhibit many beneficial effects on soil health and plant growth. While the science of biochar is still young and uncertain, many scientists around the work are engaged in research that is rapidly expanding our understanding of this class of materials and how they interact with soils.

The Nature of Biochars

Biochar is created by heating organic materials (usually plant biomass or organic wastes) to relatively low temperatures, in an enclosure without much air, so that the material smolders instead of burning with an open flame. This process is termed **pyrolysis**. The pyrolysis temperatures for making biochar range from just over 200 to about 700 °C. The biochars produced generally have high sorption capacities, variable, but often high pH, and contain many aromatic and quinone carbon ring structures. These structures are thought to be the reason why biochar readily gives up or accepts electrons in redox reactions. Biochar carbon is typically very resistant to biological or chemical degradation, making it very long-lasting in soils.

Variable Properties of Biochars

The temperature reached during pyrolysis makes a big difference in the nature of the biochar produced (Figure 20.30). Optimal biochar properties seem to result from pyrolysis

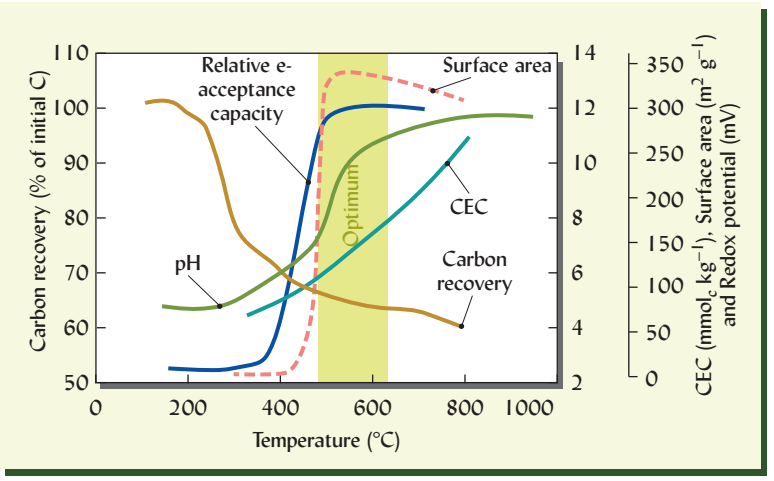

Figure 20.30 *The temperature during pyrolysis makes a big difference in the nature of the biochar produced. Optimal biochar properties seem to result from pyrolysis temperatures between 500 and 600 °C. This also happens to be the temperature range common in wildfires that produce most of the black carbon or natural char found in soils. Biochars produced in this temperature range exhibit high surface areas, high electron acceptance capacity (low redox potential), high pH, and high cation exchange capacity (CEC). These properties, in turn, appear to be largely responsible for the many beneficial effects reported to be associated with the amendment of soils by large amounts of biochars.* [Diagram based on data in Klüpfel et al. (2014) and Lehmann (2007)]

[5]For a reviews of biochar use in remediating polluted soils see Xie et al. (2014) and of the perils and promise of using biochar as an a soil amendment, see Singh et al., (2015) and Kuppusamy et al. (2016).

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temperatures between 500 and 600 °C. This also happens to be the temperature range common in wildfires that produce most of the black carbon or natural char found in soils. Biochars produced in this temperature range exhibit high surface areas, high electron acceptance capacity (low redox potential), high pH, and high CEC. These properties, in turn, appear to be largely responsible for the many beneficial effects reported to be associated with the amendment of soils by large amounts of biochars. If pyrolysis temperatures are above 700 °C, the resulting char tends to be hydrophobic and water-holding capacity and reactivity are much reduced.

In addition to pyrolysis temperature, the second major factor influencing the nature of biochars is the raw material from which they were made. Biochars made from the wood of different tree species (e.g., pines versus oaks) are quite different, but not nearly so different as grass-based biochars compared to wood-based, or biochars made from animal manure as compared to crop residues. Of course, the more nutrient-rich feedstocks generally make biochars that may benefit plants directly by supplying these nutrients. However, there are also differences in the biochar pH and redox potential as well as sorption capacities. With so many combinations of different feedstocks and pyrolysis temperatures use in making biochars, it is best to speak of the use of *biochars* in the plural rather than speak of *biochar* as if it were a universally uniform product. The diversity of properties is one reason why there are so many contradictory reports about the effects of biochars as soil amendments.

Agricultural Use of Biochars

Biochar amendment has been reported to affect plants both positively (some studies showing up to 30% yield increase) and negatively (as much as 20% yield decrease), but the beneficial impacts appear to be more common than the negative. On average, biochar has produced modest yield increases of 5–10%. In many cases, at least part of the positive impact on yield appears to result from the liming effect of the high pH biochar added to acid soils. Reported results are highly variable, but some biochars appear to enhance the supply of nutrients, especially N, P, and S to plants, but some biochars with more reactive carbon can reduce nutrient availability through immobilization. Most studies show a marked increase in cation exchange capacity and water-holding capacity in biochar amended soils. There are also reports of enhanced microbial activity, aggregate stability, and plant disease suppression.

Generally, it takes a lot of biochar to produce the beneficial effects just mentioned. Benefits to plant growth have usually been observed with biochar amendment rates in the range of 1–5% of the soil by weight or about 10–50 Mg biochar per ha. These rates of amendment might be as high as 15% on a volume basis as biochar has a bulk density of about 0.5 Mg/ m^3, which is much lower than the bulk density of most soils. Use of rates higher than 50 Mg/ha increases the chances of negative or toxic effects. Achieving the requisite high proportions of biochar can be a challenge in the field (Figure 20.31), but such amendment probably does not have to be repeated very often as the effects are largely quite long lasting. In fact, some scientists consider that one of the main benefits of adding biochar to soils is the long-term stabilization of carbon that otherwise would oxidize to carbon dioxide.

Use of Biochars Remediate Polluted Soils

High surface area and sorption capacity and large electron transfer capacity are among the properties of biochars that may allow them to aid in cleanup of polluted soils. The latter property is of particular interest with regard to organic pollutants that are susceptible to reductive degradation reactions (see Section 18.3). Biochars produced from crop residues at low pyrolysis temperatures seem to contribute the greatest amounts and variety soluble reducing compounds. With other biochars, the particle surface apparently exhibits an electron shuttle function that can enhance the chemical and biological degradation of many pesticides and other organic pollutants, as well as detoxify certain metals.

The sorption of pollutants on the biochar surface, like adsorption on clays, also has the benefit of retarding the toxic activity and mobility of contaminates while biochemical

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Figure 20.31 *Large piles of rice hull biochar await spreading and incorporating into the soil of a farm field in southern Brazil. Biochars have had the most beneficial effects when applied at high rates in the range of 10–50 Mg/ha.* (Photo courtesy of Ray R. Weil)

processes are given a chance to break them down. On the other hand, one should be aware that amendment with large amounts of certain biochars with contents of high polycyclic aromatic hydrocarbon and metals may potentially add contaminants to the soil.

20.10 ORGANIC FARMING SYSTEMS[6]

There is a growing movement to view the farm as a living system whose many component parts (plants, animals, microbes, soils, people, etc.) are integrated in an *organic* manner, that is, they act in concert as a whole organism. Hence, the term "*organic*" in **organic farming**. Although organic farming systems are quite varied, they share a central focus on soil health, as well as on the avoidance of synthetic chemicals (whether or not these chemicals are "organic" in the chemistry sense pertaining to carbon in their makeup). Food consumers, especially in rich countries, have been willing to pay more for foods they perceive to be safer to eat and of greater nutritional quality. Some consumers also favor organic products out of concern for environmental and social impacts of food production. As a result, organic farming has grown rapidly in terms of numbers of organic farms, land in organic production, and the value of organic food and drink sales (Figure 20.32). Organic food sales now accounts for about 4% of all foods sales in the United States, but about 10% of the fresh vegetables and fruits. To assure consumers that they are getting what they pay extra for, official organic farming certification and inspection programs have been developed in many countries, including a program run by the U.S. Department of Agriculture.

Scientific opinion is divided on the issue of organic food quality because the many studies that have compared organically and nonorganically produced foods have not consistently found differences in nutritional quality or safety—except that the organic food less frequently contains detectable residues of certain pesticides, and when found these toxins are at much lower concentrations. However, a carefully conducted meta-analysis that reviewed over 300

[6]For the history of the organic farming movement, see Heckman (2006, 2007). See USDA/AMS (2006) for the USDA organic farming certification program. For a rigorous assessment of food production potential (yields) of organic farming compared to nonorganic, see Barański et al. (2014) and Seufert et al. (2012). For a scientific comparison of the quality and safety of organically and conventionally grown food, see Winter and Davis (2007) and Barański et al. (2014). For organic farming prospects to fulfill food and wellbeing needs, see Reganold and Wachter (2016).

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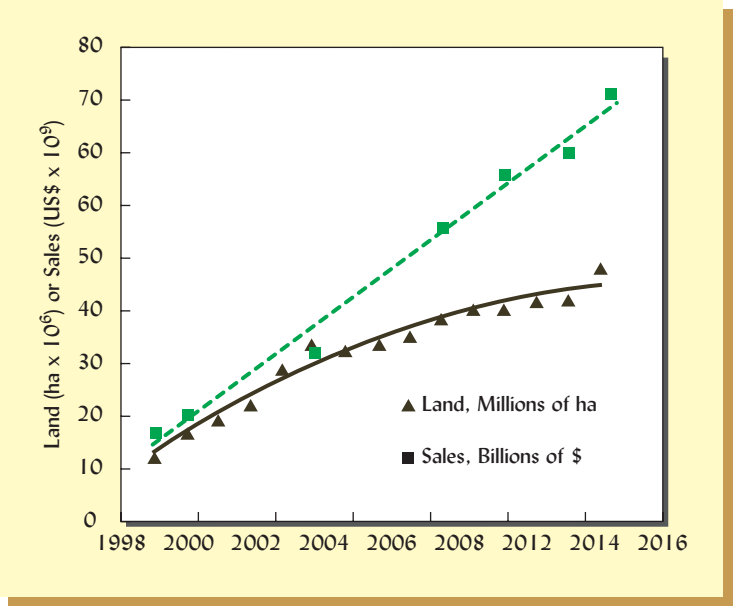

Figure 20.32 *The global sales of certified organic food and drink and the land area devoted to their production. Almost half the global sales value of organic food was in the United States. Almost half the organic certified land area is in pasture or rangeland, mainly in New Zealand and Australia.* (Graphed from data at www.fibl.org)

scientific publications on the topic and concluded that, averaged across many growing seasons and locations, there were some significant differences: organic foods were higher in beneficial antioxidants (probably because of some stresses including lower soluble nitrogen during plant growth) and significantly lower in the toxic metal Cd (possibly because some conventional farms use high rates of phosphorus fertilizers that contain Cd contamination from the phosphate rock raw material).

Most organic farmers live in developing countries. India has the most, with some 650,000 organic farms averaging less than 1 ha each in 2013. In Europe, where certification and government incentive programs have encouraged organic farming, there were some 330,000 certified organic farms on almost 11.5 million ha of certified organic farmland. In the United States, about 16,000 farms on more than 2.2 million ha were certified organic by 2013. A generation ago, many skeptical agricultural scientists and officials said it would be "impossible" to grow food on a commercial scale using organic farming methods, but the organic food now common in modern supermarkets and the thousands of organic farms that produce reasonably high yields and make good profits have proved such skeptics wrong (Figure 20.33).

Organic Farming Philosophy and Practice

At its core, organic farming is a system that strives to integrate ecologically oriented good management practices, many of which are discussed in this textbook. This orientation is expressed in the USDA regulation that governs organic farming in the United States, which states that "Production practices . . . must maintain or improve the natural resources of the operation, including soil and water quality . . . . The producer must select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion." The regulation goes on to spell out cultural practices such as rotations, cover crops, compost and manure application, companion plantings, timing of operations, use of natural enemies to manage pests, selection of crop species and varieties that are favored for the management of plant nutrition, weeds, and insects. Only when such approaches are insufficient does the regulation provide for the use of certain approved, naturally occurring chemicals. Unfortunately, regulators, consumers, and farmers too often pay more attention to the list of allowed and forbidden materials than to the broader principles of ecological farming.

No hormones, synthetic drugs, or antibiotic feed additives (see Box 11.3) are allowed in raising organic livestock. The feed for organic livestock must be from organically grown plants.

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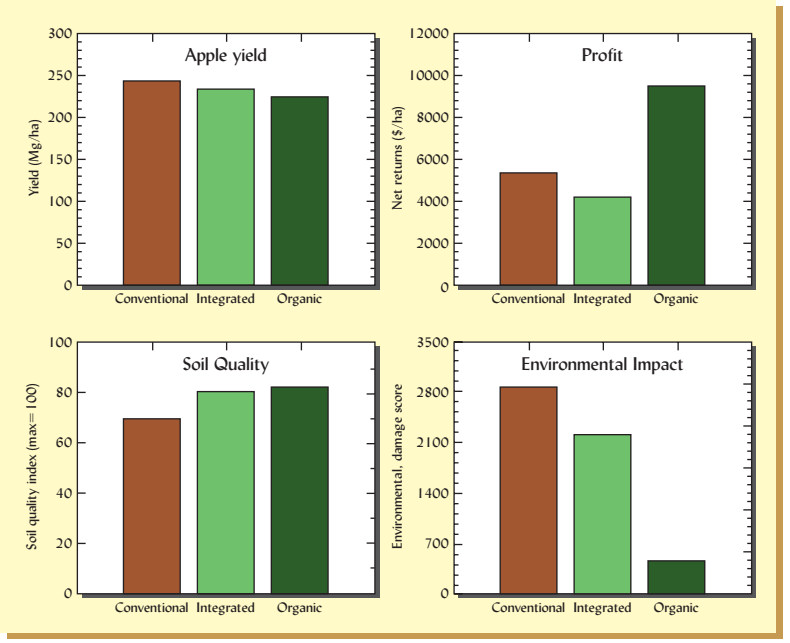

Figure 20.33 *Sustainability of three apple production systems in Washington State, USA. Cumulative apple yields during the six-year study did not differ among systems. However, the soil quality index (Box 20.1) was higher in the integrated and organic systems, which received organic amendments, compared to the conventional system using only mineral fertilizers. The profit in the final study year (which saw full-quality production for all systems) was much higher for the organic system because prices received for certified organic apples were higher and yields were good. A price premium of about 12% would be needed to allow the organic growers to recoup their extra costs. This price premium may be seen as a way that markets pay organic producers for protecting the quality of soil and water resources. Environmental impacts for the conventional apple orchard were potentially far more damaging than for the other two systems, even though this conventional system used only recommended practices and chemicals.* [Data selected from tables and graphs in Reganold et al. (2001)]

Most organic certification programs call for the seeds planted to be from organically grown seed crops and some even require the manures spread to be from organically raised livestock. The organic farming *philosophy* prohibits the use of synthetic chemicals, including most commercial fertilizers and pesticides. While the potential for adverse effects on both people and non-target organisms by the use of hormones or pesticides is well known, the *prohibition* (as opposed to the *de-emphasis*) of processed mineral fertilizers appears to have little basis in science. The aversion to mineral fertilizers in organic farming may have originated because of a belief in the "humus theory" of plant nutrition (Section 12.5) and also because of concerns that farmers were adopting cheap, easy-to-use mineral fertilizers *instead of* traditional nutrient sources such as manure and compost, rather than *in conjunction* with these organic materials. The antifertilizers strictures may also have grown out of bad experiences in the early days of fertilizers, when sodium nitrate was a popular nitrogen source. With heavy use, the sodium in this fertilizer can cause deterioration of soil structure (see Section 10.6), accounting for the description of soils so treated as "hard and lifeless." Ironically, naturally occurring (but equally damaging) sodium nitrate materials are among the few soluble mineral fertilizers allowed by some organic certification programs.

To maintain soil fertility, organic farmers (who do not speak of fertilizing crops, but rather of "feeding the soil") utilize organic materials and naturally occurring, unprocessed mineral sources of plant nutrients. While animal manures are commonly used on both organic and nonorganic farms, on the certified organic farms the timing of their use is regulated to avoid problems with human pathogens contaminating food products. For example, organic certification prohibits application of raw manure to fields within 90–120 days of vegetable crop harvest. Organic farms also may use the nutrients in such sources as cover crops, crop residues (particularly of legumes), and powdered rocks (such as phosphate rock and greensand).

Organic Versus Conventional

Researchers have conducted hundreds of studies in which organically managed farms or plots (usually following certification programs) are compared to those that are not managed organically. Most often the nonorganically managed systems are termed "conventionally managed." However, experiments designed to compare the yield performance of organic to conventional farming are of dubious scientific value because "organic" is largely defined by regulatory rules made by committees on philosophical and political as well as scientific bases and

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"conventional" could mean almost anything (other than strict adherence to the organic rules). In addition, such comparisons rarely give us any indication of *why* any observed differences in performance may have occurred, indications that could assist in making improvements in future farming systems. However, the "organic versus conventional" question has been raised so often because important policy implications may derive from the answer.

Organic systems can be promoted as a serious answer to our environmental and soil health concerns only if they also address our food security concerns. The comparison therefore centers on both yields and soil health. If average yields are lower for organic systems, then it can be justly asked if one is willing to make the additional conversions of natural forest and savannah habitat into cropland that would be required if organic replaced so-called conventional systems as the major means of feeding the world's growing population.

In some cases, organic farms have been observed to produce declining yields, deplete soil nutrients, or even allow greater nutrient leaching than their conventional counterparts. However, other studies show the opposite: on farms that convert to organic management yields increase over time, long-term soil fertility is maintained, and soil quality is enhanced.

As with conventional farms, some organic farms perform better than others. It is difficult to objectively compare whole farming systems because they differ in so many inputs, outputs, and processes. For example, a conventional 500 ha grain farm may sell just two crops, say corn and soybeans. A neighboring 500 ha organic farm would be likely to grow wheat, barley, oats, alfalfa/grass hay, beef cattle, and sheep in addition to some corn and soybeans. Even when more limited comparisons are made on research station plots, objectivity can be compromised if the managers of the research farm are themselves more experienced and skillful in managing one system or the other. With these limitations in mind, most research studies comparing systems *with similar tillage practices* show that organic farms produce far less pollution and adverse environmental effects than do their conventional counterparts. Since no feed additives, antibiotics, or synthetic pesticides are used in the organic systems, the difference for environmental protection is most obvious with regard to residues of such chemicals on produce and in runoff and groundwater. In some comparisons, organic farming also reduces erosion, nutrient leaching, and runoff. Organic farming may have positive effects on soil quality, especially if compared to a farming system that uses the same tillage, but without comparable organic matter inputs from crop rotations and applied compost or manure (Figure 20.33 and Table 20.8).

In research plot comparisons, organically grown crops often yield 10–30% less than those grown conventionally, depending on what systems are compared (Figure 20.34).

Table 20.8
EFFECTS OF CONVENTIONAL AND ORGANIC-BASED CROPPING SYSTEMS ON SELECTED SOIL QUALITY INDICATORS AT THREE LOCATIONS IN NEBRASKA

The conventional systems involved continuous corn or corn–soybean rotation with inorganic fertilizers. The organic systems involved 4–6 crops in rotations that included 2–5 years of alfalfa, and crop residues and manure (from livestock fed the alfalfa) as the main sources of nutrients. The organic systems, that is the more diverse rotations, generally resulted in higher indicators of soil quality.

	Giltner NE (Udic Argiustoll)		Valley NE (Udic Argiustoll)		Deweese NE (Typic Haplaquoll)	
Soil quality indicator	**Conv.**	**Organic**	**Conv.**	**Organic**	**Conv.**	**Organic**
Bulk density, Mg/m^3	1.34	1.26	1.35	1.08	1.22	1.18
Water-holding capacity, m^3/m^3	0.15	0.17	0.15	0.21	0.18	0.20
pH	5.93	6.25	4.96	6.46	6.12	6.59
Organic C, Mg/ha	53.4	55.6	42.34	57.92	55.57	70.28
Microbial biomass C, kg/ha	651	816	464	775	654	1192

Selected data from Liebig and Doran (1999).

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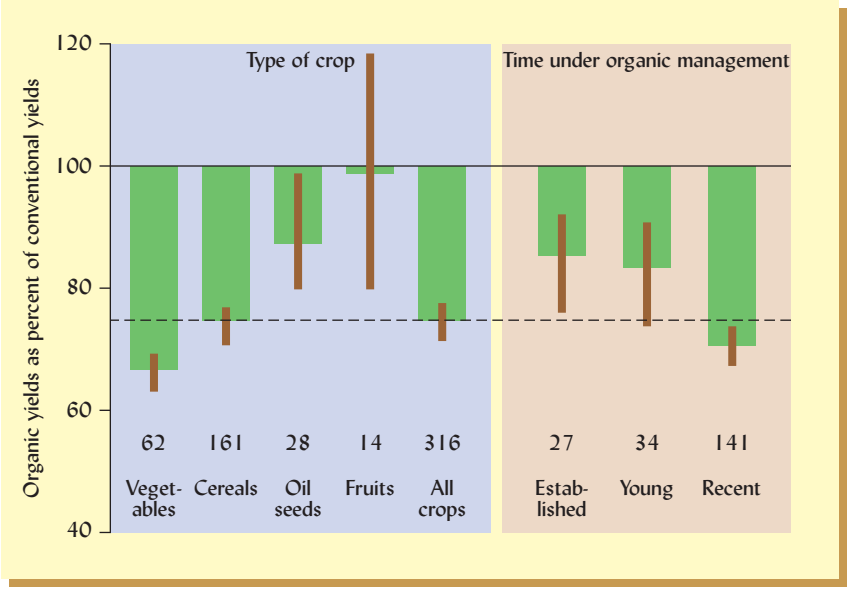

Figure 20.34 *Using data from 316 published scientific studies organic methods, on average, produced yields that were about 75% of the yields produced using so-called conventional methods (*all crops *bar). However, the difference in yield between the systems was quite a bit smaller for some types of crops than for others. Also, the longer the organic system had been in operation, the closer the yields were to those in the conventional system* (Right). *The numeral above each category is the number of comparisons contributing to the average.* [Modified from several graphs in Seufert et al. (2012)]

However, studies comparing commercial farms usually show that farmers well experienced in using organic or conventional methods generally produce similar yields per hectare of certain crops, such as tree fruits and legume seeds. Moreover, the organic farmers often make a greater profit. The enhanced profit is sometimes due to lower costs for such inputs as fertilizers and pesticides, but more often the greater profits result from premium prices that consumers are currently willing to pay for organically produced food (Figure 20.33).

Organic Versus Sustainable

It should be understood that *organic* does not always mean *sustainable*. For example, organic farms that rely on off-farm feed for their animals or use off-farm manure and compost for soil fertility may be challenged to avoid the nutrient pollution described in Sections 16.1 and 16.2. Many organic farms apply rates of manure and compost that result in a long-term buildup of environmentally excessive amounts of mineralizing N and P. Enhanced soil quality in organic systems stimulated by the use of these amendments may also come at the expense of other soils, perhaps on another farm, that become depleted because the manure and residues generated by that land have been removed.

A related sustainability problem is the negative nutrient budget (Section 16.1) maintained by some organic farms, especially with respect to phosphorus. Some organic farms that were established on land that had previously accumulated high levels of phosphorus (Section 14.2) have been able to maintain high yields for years or even decades despite the fact that they export more P in products sold than they import in phosphate rock or other materials. However, eventually this imbalance results in P deficient soil that limits productivity. Furthermore, because available supplies of phosphorus and other nutrients are finite Section 16.4), we must eventually learn to achieve a high level of nutrient recycling in our entire food system, whether or not it is managed with organic farming methods. A step in this direction is suggested in Box 20.2.

Perhaps the most serious sustainability limitation for organic farmers is that they cannot easily adopt conservation tillage practices that minimize soil disturbance and enhance soil health (Section 17.6) because such practices generally depend on prohibited herbicides for weed control and for cover crop termination. Therefore, organic farms may suffer more soil erosion, biodiversity disruption, and soil quality degradation than farms that use the best available no-till and other conservation tillage practices, along with some use of agrichemicals prohibited by organic rules (Figure 20.35).

To overcome this problem, researchers are attempting to develop "organic no-till" cropping systems for use on erodible soils. One approach uses tall high-residue cover crops that are killed without herbicides and without tillage using special roller-crimper machines (see

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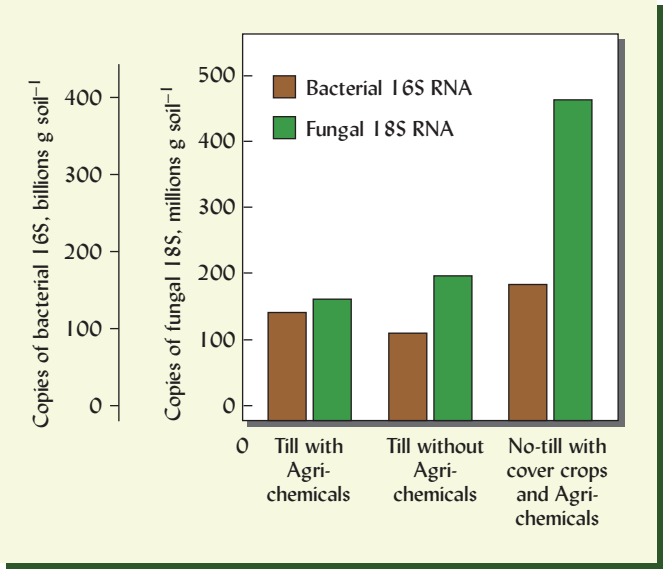

Figure 20.35 *The influence of agrichemicals and tillage on the soil bacterial and fungal communities in a wheat–rape–pea crop rotation the Paris Basin, France. The first system (left) might be considered conventional (moldboard plowed annually, very high rates of inorganic fertilizer (averaging 520 kg N, 100 kg P, and K ha^{-1} yr^{-1}) and synthetic pesticides used as needed to control disease, insects, and weeds. The second system was essentially organic management. It used the same rotation and soil management as the first, but without chemical fertilizers or pesticides, and with an additional legume crop (pea) every fifth year to add fixed N for the other crops. The third system (right) used the same crop rotation and chemicals as the first, but without any tillage (no-till) and with cover crops during the off season. The main effect found here, as in many other studies, was that tillage greatly reduced fungal populations (as measured by copies of 18S RNA). The silt loam Eutrudept soil (upper 6 cm) from the no-till system also had greater organic carbon and nitrogen contents and water holding capacity than the soil from the other two systems (data not shown). This layer was sampled as it is the depth most influenced by agricultural practices.* (Graphed from data in Kaisermann et al. (2013))

Figure 16.31). No-till equipment then plants into the rolled cover crop residues, which are meant to form a thick mat that controls weeds without herbicides and without subsequent soil-disturbing cultivation. One problem with this method is that only certain cover crop species can be effectively killed by rolling, and the plants need to be in an advanced state of maturity. Waiting for this stage may postpone the planting of the cash crop, so the system is best adapted for crops that do well when direct seeded or transplanted quite late in the growing season.

A second organic no-till cover crop approach is best adapted to temperate or cold region crops that need to be planted very early in the season. In this approach, a cover crop is chosen that will grow vigorously in the fall and into early winter to suppress the germination of early spring weeds, but will then be killed by subfreezing temperatures. Moreover, this cover crop should decompose quickly so the soil is bare enough to warm up and dry out quickly after the spring thaw. This system appears to work well when a forage radish cover crop is planted in early fall and vegetables such as lettuces, spinach, peas, or carrots are planted in early spring (Figure 20.36). In both of the just described "organic no-till" systems,

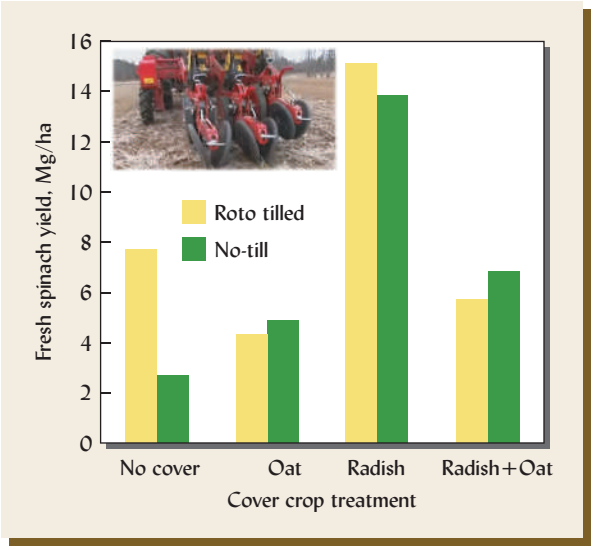

Figure 20.36 *Reducing the use of tillage presents a challenge for organic vegetable production. In temperate regions, winter-killed cover crops such as forage radish can provide a suitable seedbed for no-till planting of early spring vegetables like spinach, without the use of herbicides or spring tillage. The standard organic vegetable production system would be the tilled, no-cover combination (far left). The oat cover crop winter killed but did not suppress weeds sufficiently and left too much surface residue for early warming and drying of the seedbed. Photo inset shows no-till planting of spinach into decayed forage radish residue in early spring.* [Photo courtesy of N. Lounsbury, University of Maryland. Graph based on data from Lounsbury and Weil (2015)]

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BOX 20.2

THE LAW OF RETURN MADE EASY: USING HUMAN URINE[7]

A central tenet of organic farming—of any good farming, really—is the Law of Return which states that all the nutrients that a plant takes away from the soil should be returned to the soil to complete the cycle, prevent soil depletion and resource exhaustion. The return of nutrients to the land is paid lip service, but rarely implemented. Instead, in almost every culture children are inculcated from a young age to believe that human wastes are disgusting, not to be discussed and to be completely avoided. These attitudes are justified regarding excrement, since feces carry high concentrations of human pathogens, are difficult to handle cleanly, and smell pretty awful. Although often carelessly mixed with feces, urine could not be more different. It is generally free of pathogens because it has been filtered through the kidneys. Furthermore, if it is contaminated with pathogens, storing it in a closed container for a week will cause it to self-sterilize via the ammonia it releases. It is easy to handle, and if kept clean, does not smell very much. But its main virtue is that it holds in dissolved, plant-available form, most of the mineral nutrients that were in a person's diet. Tests have shown that food harvested from urine-treated plots does not have greater bacterial contamination than food conventionally grown. Research in Nigeria has shown that people are willing to buy urine-fertilized produce. One question that needs research is: what happens to pharmaceuticals or natural hormones excreted in the urine once they are applied to soil? For that matter, little is known what happens to these chemicals when they are flushed down the toilet.

Urine is essentially a liquid fertilizer solution that we all make from our food and drink. More than half of the N ingested is excreted in the urine. It also contains significant amounts of K, P, S, Ca, and Na and smaller amounts of Mg and micronutrients (Table 20.9). In addition, urine is very easy to collect. Just keep a plastic jug with a suitable wide opening next to the toilet (Figure 20.37a). Or for large-scale

Table 20.9
PLANT NUTRIENTS IN HUMAN URINE

Plant nutrient	Concentration in urine mg/L
Total nitrogen	2500
Ammonium -N	2200
Total phosphorus	170
Potassium	1200
Sulfur	130
Copper	0.30
Manganese	5.2
Magnesium	0.82

Urine from 100 inhabitants of Demark analyzed by Kolby and Jansen (2003).

Figure 20.37 *Simple means of collecting and using human urine. (a) Everyone can have a jug with their name on it. (b) Lawn grass responds to the nitrogen (and other nutrients) in the diluted urine that was applied in the shape of the letter "N." The area around the letter received only water. (c) A backyard experiment in Africa using compost to fertilize the row of cabbage plants on the left and compost with urine on the right.* (Photos (a) and (b) courtesy of Ray R. Weil; photo (c) courtesy of Ben Waterman)

[7]The use of human urine as fertilizer has been the subject of a limited amount of research (AdeOluwa and Cofie, 2012; Heinonen-Tanski et al., 2010; Karak and Bhattacharyya, 2011; Pradhan et al., 2007; Richert et al., 2010; Shrestha et al., 2013; Wilsenach, 2006).

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BOX 20.2
THE LAW OF RETURN MADE EASY: USING HUMAN URINE *(CONTINUED)*

urban collection, one can tap men's urinals or install separator toilets designed such that urine goes down one tube while feces and paper go down another. Several towns in New England, USA and in northern Europe have organized themselves to provide urine in bulk to local farms.

So why would typical Westerners use 20 to 80 L of drinking quality water to flush away every liter of urine they produce? Why would subsistence farmers waste their urine behind the bushes or in the latrine? The answer in both cases is that they generally do not know any better. Many small-scale farmers and gardeners have probably tried urinating on a tomato plant or the like and noted that the plant was injured, possibly even killed. Yes, and a concentrated fertilizer solution poured onto a plant can also burn the plant. The problem is concentration; the osmotic potential or salinity is too high (see Sections 5.3 and 10.7). Before applying urine to plants, one needs to dilute it: one part urine in two parts water. When applied to moist soil without young plants, a 1:1 dilution is safe.

Another great way to recycle the nutrients (and water) in urine is to add it to one compost pile, especially if the main material is dried leaves or other brown plant residues. The results can be dramatic: the pile will heat up rapidly as the moisture and especially the nitrogen is used by bacteria to metabolize the residues.

Annually, about 2.5–4 kg of N could be collected per capita from urine as the average urination rate is about 2 L/day and the human urine contains between 1 and 8 g N/L. Urine is also an excellent source for potassium, sulfur, and phosphorus. To put this in perspective, a family of six would be able to fertilize about 0.25 ha of crops if they collected and used all their urine (assuming a moderate per ha fertilization rate of about 70 kg N, 35 kg K, and 6–12 kg P and S per ha. Likewise, a suburban family of four could easily keep their lawn and garden green without purchasing any fertilizer, but using only diluted urine (Figure 20.37c). Not to mention that they would significantly reduce their water use and eliminate 60% of the N they send to the water treatment plant.

tillage is used to establish the fall cover crops, so neither system actually complete no-till. However, such systems show that the ill effects of tillage can at least be reduced while still adhering to organic rules.

20.11 SUSTAINABLE AGRICULTURE SYSTEMS FOR RESOURCE-POOR FARMERS

Some 800 million people in the world still do not have enough food to eat (Figure 20.38). Most of these undernourished people are in rural families that depend on the food they can grow themselves. Hundreds of millions of poor people in developing countries practice low-yield subsistence farming by which—in a *good* year—they barely eke out sufficient food to keep their families alive. Most have little or no extra production that they can sell to earn the cash that could enable them to pay school fees for their children or purchase fertilizers, improved seeds, or livestock to enhance their farm. Many are shifting cultivators (Section 20.7) trapped in the downward cycle of soil degradation (see Figure 17.2) because they no longer have enough land to allow the fallow periods needed for natural soil rejuvenation. Some who can afford small amounts of fertilizer use it to grow cash crops like cotton or coffee that will repay the cost of the fertilizer and yield a small cash profit, but such crops will not feed their families. Typically, to produce enough calories to stave off hunger, these farmers devote nearly all their land to the production of a starchy staple crop such as corn, sorghum, cassava, or rice. This leaves little land for more protein-rich pulses such as beans, cowpeas, lentils, or pigeon peas. Commonly, women may tend a small kitchen garden area immediately next to the house where leafy vegetables, root crops, herbs, and sometimes pulses are grown to provide some balance and variety to the family diet. Innovative systems that are more productive and sustainable but that require very little cash investment are needed to lift the lives of hundreds of millions of people trapped in such circumstances around the world, and especially in Africa.

To illustrate how food production, income generation, and soil quality might all be enhanced in currently low-yield, resource-poor areas, we will focus on the situation in

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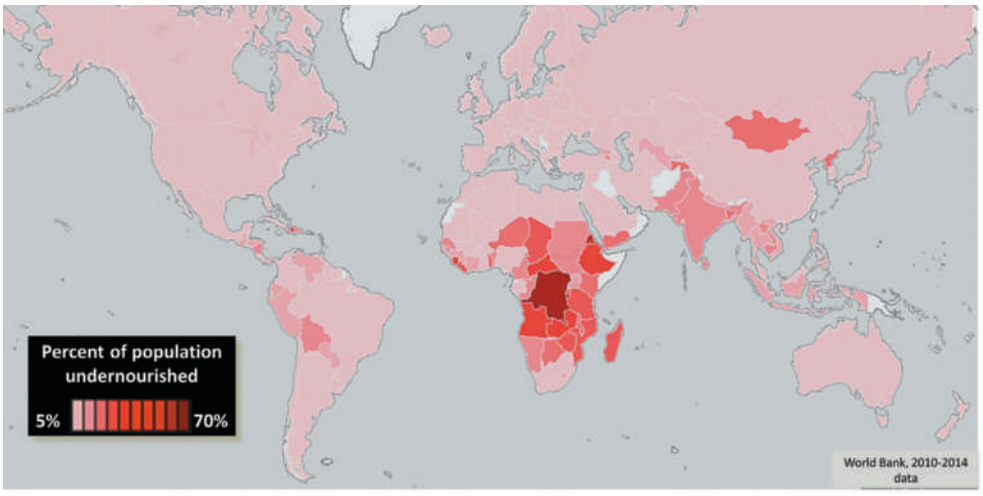

Figure 20.38 *The percent of people in various countries suffering from too little to eat (undernutrition) during the period 2010–2014. The Green Revolution of the 1970s and the Asian economic boom of the 1990s and 2000s greatly reduced hunger in Asia and South America (which now show only a few countries in dark red). However, in sub-Saharan Africa the proportion of the population suffering from undernutrition dropped from 33% to 24%, but the absolute number of people affected actually increased during the past three decades.* (Mapped from World Bank data at http://data.worldbank.org/indicator/SN.ITK.DEFC.ZS/countries?display=map)

sub-Saharan Africa. However, the principles discussed here also apply to low-productivity agricultural systems in many other tropical areas.

Improving Soil Quality in Sub-Saharan Africa[8]

About 55% of the land area of the African continent is considered unsuitable for any kind of agriculture except nomadic grazing, yet some 30% of the continent's people eke out an existence in these areas. Soils of low quality are found on an additional 16% of Africa's land base, where 23% of the people live. These soils are limited by such constraints as extreme acidity, impermeable layers in the subsoil, and accumulation of salts. Fortunately, medium- to high-quality soils are found on about 30% of the land where 47% of the people live. These soils are free of major constraints and are found in regions where rainfall is stable and sufficient for at least one crop a year. They offer great potential for increased production of food and fiber; if sustainable, intensified systems can be utilized.

Nutrient Balances and Fertilizers[9]

As mentioned in Section 20.4, the high-yield, intensive agriculture of the Green Revolution increased food production and thereby the nutritional status of people in most regions of the world, except sub-Saharan Africa (Figure 20.38). The reasons that Green Revolution technologies failed to take hold in Africa are complex (including lack of effective political support, poor infrastructure, and difficult climatic and soil conditions), but an important factor was the lack of effective programs to encourage the use of fertilizer (Figure 20.39). In most of sub-Saharan Africa, as in many of the more remote, marginal lands of Asia and South America, a primary problem is deficiency of plant nutrients. Soils are simply being mined of plant nutrients, because removal by crop harvest, burning of residues, and leaching far exceeds the amounts being returned from all sources. Nutrient input/output studies on farm lands of sub-Saharan Africa show an alarming *negative balance*, suggesting a decline in soil quality (Table 20.10). Fertilizer applications average less than 10 kg/ha, and in many cases are zero. During the last 40 years, the average ha of cultivated land in sub-Saharan Africa has suffered a cumulative loss of some 800 kg N, 100 kg P, 200 kg S, and 500 kg K.

Soil acidity, deficiency of nutrients, and other soil constraints are prime reasons for low productivity in Africa and many other regions as well (Table 20.11). The quality of soils is declining annually, and this decline will continue if improvements cannot be made in soil management. Farming systems that improve nutrient cycling, maximize biological N fixation,

[8]Our use of the term *sub-Saharan Africa* does not include South Africa, which has a large, modern agricultural sector. For background on soil quality and food production systems in Africa, see Tully et al. (2015), Buresh and Sanchez (1997), and Eswaran et al. (1997).

[9]For a summary of the need for replenishing Africa's soils to alleviate poverty, see Sanchez and Swaminathan (2005).

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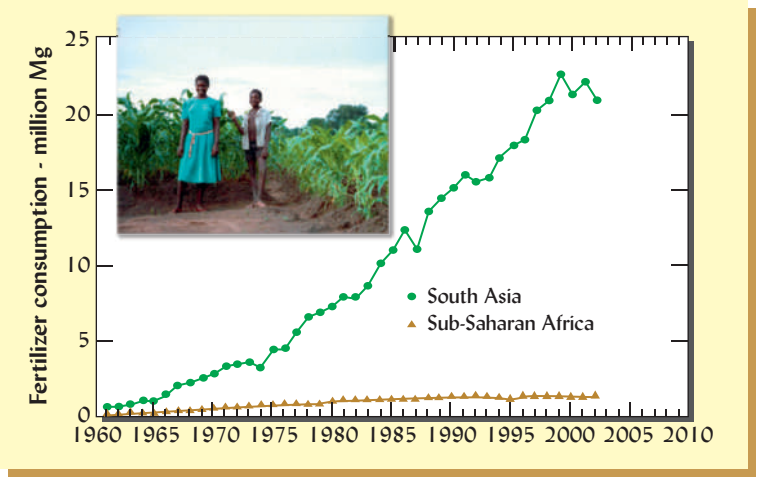

Figure 20.39 *Changes in fertilizer consumption in South Asia (India, Bangladesh, and Pakistan) compared to that in sub-Saharan Africa. The rapid rise in the use of fertilizer in South Asia reflects the influence of the Green Revolution that took hold beginning in the late 1960s and solved that region's overall food shortage problem. Unfortunately, no such progress was made in sub-Saharan Africa. The inset photo compares two corn fields on an African farm, one with and one without fertilizer applied.* (Data from FAO (2006b))

Table 20.10
AVERAGE ANNUAL N, P, AND K BALANCES (INPUTS MINUS OUTPUTS) FOR THE ARABLE LAND IN SEVERAL AFRICAN COUNTRIES

	Balance, kg/ha/yr		
Country	**Nitrogen (N)**	**Phosphorus (P)**	**Potassium (K)**
Malawi	–67	–10	–48
Ethiopia	–47	–7	–32
Senegal	–16	–2	–14
Average of 13 African countries	–39	–5	–30

From Stoorvogel et al. (1993).

Table 20.11
PERCENTAGE OF SOIL AREAS IN FIVE AGROECOLOGICAL REGIONS OF THE TROPICS HAVING DIFFERENT CHEMICAL CONSTRAINTS TO AGRICULTURAL PLANT GROWTH

Soil constraint	Humid tropics, %	Acid savannas, %	Semiarid tropics, %	Tropical steeplands, %	Tropical wetlands, %	Total, %
Acidity with Al toxicity	56	50	13	29	4	32
Acidity without Al toxicity	18	50	29	16	29	25
High P fixation by Fe oxides	37	32	9	20	0	22
Low CEC	11	4	6	—	—	5
Salinity	1	0	2	0	7	1

More than one kind of constraint may apply, so percentages do not add up to 100%. Data from Sanchez and Logan (1992).

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and protect soils from erosion are an important part of the solution. However, in many areas of the tropics, the addition of nutrients from external inputs (mainly fertilizers) will be needed to jump-start severely nutrient-depleted systems.

Fortunately, because West Africa has natural gas resources (needed to make nitrogen fertilizers) and a number of African countries have significant phosphate rock deposits (the raw material for phosphate fertilizers), the development of African fertilizer manufacture capacity is beginning to take shape. Yet it still lags far behind the need. Because of the high costs of importing fertilizers from distant factories in Europe, Asia and North America, and because of the poor transportation infrastructure (many secondary roads are too muddy for trucks to pass during the rainy season when crops are planted), the price of fertilizer in Africa is often double or triple the world price by the time it is delivered to farmers. Furthermore, the fertilizer often arrives too late for use on that season's crop. All this discourages farmers from making nutrient additions, especially in remote areas such as those where shifting agriculture is practiced. Clearly there is a need for more rapid development of the indigenous fertilizer manufacturing industry and delivery infrastructure. There is also the need for innovative practices that combine organic and inorganic nutrient sources to help stretch fertilizer supplies, to increase nutrient and carbon inputs, and to cycle the nutrients once they reach the soil.

Improved Internal Cycling of Nutrients

While nutrient losses from the whole farm or agroecosystem are very important, nutrient transfers within the farm or agroecosystem can also have critical impacts (Figure 20.40). Studies of African village farming systems show that nutrients tend to move out of the common grazing lands, forested fallows, and main crop fields (which are usually some distance from the farmers' houses) toward the house compounds in the form of firewood brought home for cooking fires, residues left from grain crops brought to the home for threshing, crop residues and tall grasses brought home for thatching roofs, manure from livestock confined near the home compound overnight, food preparation wastes, and of course, human wastes. In contrast there are almost no transfers going in the opposite direction to replenish nutrients in the source areas. As a result, the soil immediately surrounding the house is usually highly enriched in nutrients.

Many villagers take advantage of this island of fertility by growing a productive kitchen garden. However, this enriched area is very small and the soil in it is so overenriched in certain

Figure 20.40 *Recycling of nutrients is an essential component of sustainable farming. It is especially critical in developing countries for poor farmers who cannot afford to import enough fertilizer to their farms to replace all the nutrients removed from their soils by cropping, grazing, and forest harvest. The background photo shows a village in Wolayta, Ethiopia, where by local traditions people compost household wastes and reuse the nutrients in their kitchen gardens. However, most of the nutrients in the household originally came from outlying cropland (via harvested food and crop residues), forests (via firewood collected for cooking), and pastures (via manure from cattle kept overnight in the home compound). Over time, the tiny home gardens flourish while soil in the more distant croplands, pastures, and forests become depleted and degraded.* (Diagram and photo courtesy of Ray R. Weil)

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nutrients that adding more is just a waste. A few farmers attempt to move some nutrients from the home to the main outlying fields by scraping up the manure from the animal confinement area and carrying it (in head baskets or in ox carts) out to the field. However, it must be remembered that cattle manure in general has low concentrations of nutrients, especially phosphorus. Manure from African cattle grazing a low-quality diet of P-deficient forages and crop residues typically contains far lower concentrations of P and other nutrients compared to textbook values for cattle manure generated in the feedlots of developed countries. This means that many bulky, heavy loads of manure are needed to supply a modest quantity of nutrients. Moving the manure is so laborious that, in reality, very little manure ever gets transferred to the depleted outlying fields, and little or none to the depleted pasture areas where the bulk of the nutrients probably originated.

Composting the manure along with any excess crop residues has the potential to reduce the mass that needs to be carried back to the outlying fields, but is also laborious and only rarely practiced. An important but generally overlooked pool of nutrients indigenous to resource-poor village agroecosystems is the ash from cooking fires. Since it is very lightweight and relatively concentrated in certain nutrients, enough ash to replenish at least some of the depleted soils could easily be transported from the home to outlying fields (see Box 20.3).

Crop Residues and Livestock in Farming Systems

The dry stalks and husks (crop residues) left over after the removal of crop harvests might seem quite valueless, and indeed are often referred to as "trash" or "wastes." But in reality, these materials constitute the *plant litter* of the agroecosystem, and it is critically important that they be managed so they can help enhance soil organic matter, nutrient cycling, and erosion control. Just as they do in natural ecosystems, large herbivore animals can also play critical

BOX 20.3

NUTRIENTS TO BURN? AN OVERLOOKED SOURCE OF FREE FERTILIZER

Wood cut from trees, bundled crop residues, and cakes of dried animal manure are the principal sources of energy for cooking (and heating) in sub-Saharan Africa and other developing areas (as illustrated for Ethiopia in Table 20.12). Most of this biomass fuel is burned in open cooking fires that produce food flavored by smoky fragrances, as well as warmth and light to sit around in the evening. But the open fires are notoriously inefficient and require many hours of labor—usually by the women and girls of a village—to gather the fuel from distant forests or fields and carry it home (often several kilometers). Except for N, most of the nutrients in the firewood end up in the ashes.

Table 20.12
National and Per-Capita Use of Organic Materials as Fuel for Cooking in Ethiopia
Burning this biomass will produce ashes weighing about 2% of the initial dry mass.

Type of fuel	Mg × 10^6	Mg/person[a]
Wood	21.4	0.52
Manure (Dung)	15.4	0.41
Crop residues	9.6	0.21
Total	46.4	1.14

[a]National fuel use/national population in 1990. Fuel demand estimates for 1990 from Girma (2001)

By early morning, when the fire has burned out, the women can be seen sweeping the now cool ashes just beyond the living compound into the kitchen garden where the soil is already overenriched from countless previous ash additions. In some cases, ashes may be used to reduce odors in the family pit latrine. But it is very rare to find a villager who collects the ashes in a place where they are protected from rain and then spreads them evenly over the most distant fields where soil fertility is the lowest.

The statistics for Ethiopia indicate the potential significance of this nutrient resource. Rural Ethiopians annually burn an average of about 0.52, 0.41, and 0.21 Mg dry weight of wood, crop residue, and cattle manure (for a total of 1.14 Mg dry biomass used as fuel per person). Ethiopia has about 1/6 ha arable land per person in the farming population. Thus, for each hectare of cropland there are six people burning approximately 6840 kg (6 × 1.14) of total dry biomass per year.

Depending somewhat on the tree species, animal feed, and fertility of cropland, this dry matter will produce ashes weighing about 2% of the initial dry mass, or about 137 kg (0.02 × 6840 kg) of ash per six people or per ha of available cropland. Using the nutrient concentrations from

(continued)

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BOX 20.3

NUTRIENTS TO BURN? AN OVERLOOKED SOURCE OF FREE FERTILIZER *(CONTINUED)*

Figure 20.41, for every ha of available cropland this ash would contain 1.3 kg P (137 kg ash × 0.0095 kg P/kg ash), 0.75 kg S, 6.7 kg K, and 13 kg Ca, plus small but significant quantities of micronutrients. If protected from rain (the nutrients in ash are water soluble) and spread where most needed on 1/5 of the cropland, the application rates would be five times the rates just cited, or 6.5 kg P/ha, 3.8 kg S/ha, 33.6 kg K/ha, and 65 kg Ca/ha. This rate of ash application would supply sufficient nutrients to at least arrest the acidification process and replace nutrients removed by crop harvest and leaching (compare to negative balances given in Table 20.10).

The use of ash might produce substantial gains in crop productivity as suggested by the responses of faba bean and wheat shown in the bar graph (Figure 20.41). The ash might be best utilized first on leguminous crops or trees, in order to leverage the P, S, K, and Ca fertility into added nitrogen via enhanced biological N fixation. The value of the ashes might be further enhanced if modest amounts of N and P fertilizers could also be applied (but mixing the high pH ashes with these fertilizers should be avoided! See Sections 13.6 and 14.7). Another option to provide N would be the collection of human urine, which could supply as much as 50–90 kg N/ha on 1/5 of the available cropland each year (Box 20.2).

In this example, the nutrients do not represent *additions* to the agroecosystem. Rather, the use of ashes represents mainly a *transfer* of nutrients within the agroecosystem: to the croplands from woodlots, hedges, and common grazing areas. The fields farthest from the house are usually the most depleted in all nutrients and so they are the fields where the greatest response to ash application might be expected. The cost to the farmer of utilizing this currently wasted resource would be very low in terms of both cash and labor, so even small, short-term crop responses could make the practice attractive.

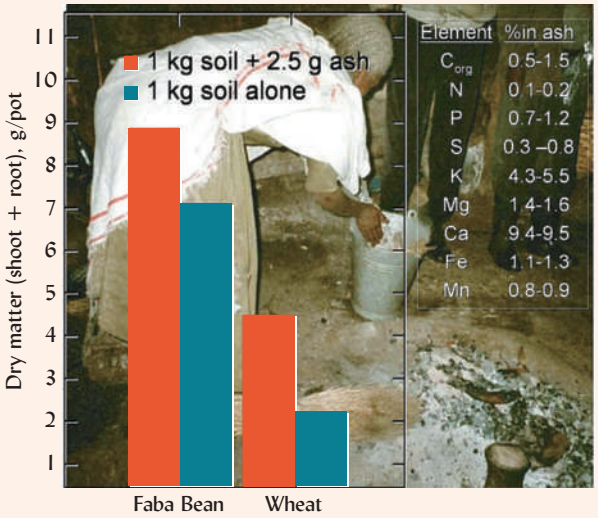

Figure 20.41 *Nutrient concentrations (ranges upper right) found in ashes from several villages in the Ethiopian highlands and responses to the ash by faba bean and wheat plants (graph) grown in an acid (pH 5.5) soil from a degraded outlying crop field. In the background an Oromo woman collects ashes from her cooking fire to give to researchers.* (Unpublished data of Ray R. Weil and Asgellil Dibab; photo courtesy of Ray R. Weil)

roles in agroecosystems, by recycling nutrients and organic matter in the very beneficial form of animal manure and by encouraging land uses that include stands of grasses and legumes, which also help build soil quality. In developing countries, livestock (oxen, donkeys, horses, and buffalo) also provide traction power—playing the roles that tractors do in more industrialized-country agriculture. For animal agriculture to be integrated with crop production in a manner that builds rather than degrades soil quality and farm productivity, there must be a balanced relationship among such major system components as livestock grazing, animal traction, tillage intensity, pasture grazing, forage crops, food crop residues, animal manures, and fuel wood trees (see Figure 20.42).

For example, if a farming system involves large amounts of tilled land with many sequential tillage passes performed each year, farmers will desire a relatively large ratio of draft animals to land area (Figure 20.42). The draft animals (and associated livestock for breeding replacements) require large amounts of fodder, often in the form of crop residues. Farmers either collect the crop residues for use as dry season livestock feed, or they allow the livestock to graze the residues in the fields after harvest (the latter practice at least returns some nutrients and organic matter as manure dropped during grazing). In either case, the soil is deprived of the residue cover it needs to counter erosion and organic matter depletion.

Introduction of a reduced-tillage farming system might contribute to the solution from the demand side by reducing the number of oxen required for tillage and therefore allowing more crop residue to be left as mulch to prevent erosion and build soil quality. From the

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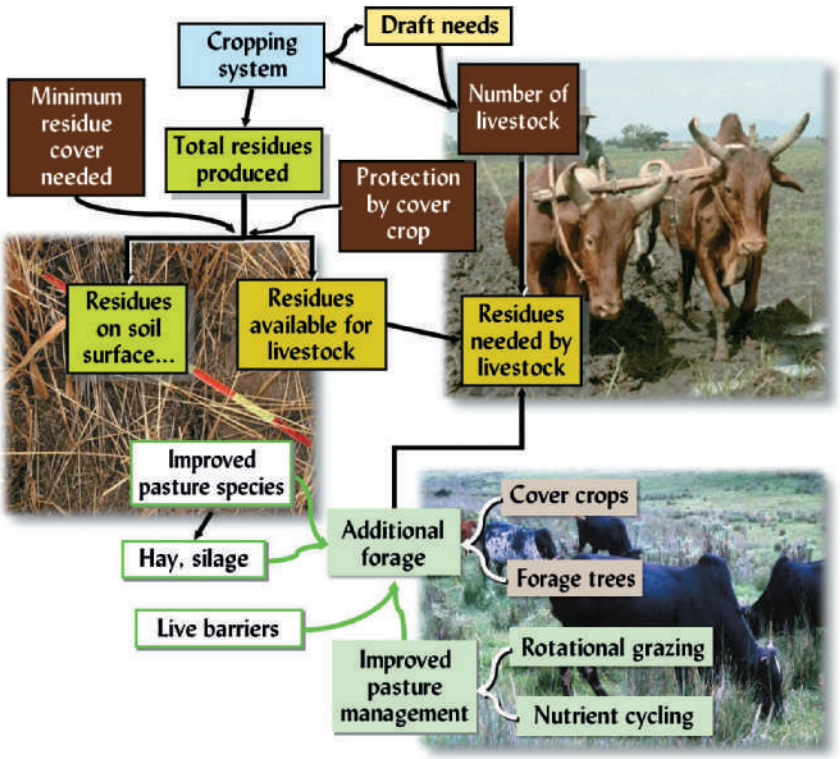

Figure 20.42 *For most farmers in Africa, livestock are an integral part of farming. In many areas oxen are used for draft power in plowing the soil to prepare the fields for sowing seed. A cropping system that uses large amounts of tillage will require many oxen (and breeder cattle), which eat large amounts of fodder, often in the form of crop residues, thus depriving the soil of the vegetative cover it needs to counter erosion and organic matter depletion. A reduced-tillage system could reduce the number of oxen required for tillage and therefore allow more crop residue to be left as mulch to prevent erosion and build soil quality. More livestock feed from improved management of pasture areas could also help support the cattle without removal of crop residues from the soil. The situation is often complicated by additional competing demands for crop residues as fuel and as material for roofing and fencing.* [Many of these concepts are reviewed in FAO (2000); diagram and photos courtesy of Ray R. Weil]

supply side, improved pastures could provide much more fodder than typically unmanaged and overgrazed common areas. Pasture productivity can be vastly increased by interseeding forage legumes in pastures (if legumes are not naturally already in the soil seedbank) and systematically rotating grazing animals from one area to another to allow forage plants in each area time to recover after periods of grazing. Pastures can be further enhanced by relatively small applications of nutrients, especially phosphorus, and on some soils, potassium. These nutrients are known to stimulate greater biological N fixation by pasture legumes, the fixed N in turn stimulating growth of both the legumes themselves and associated grasses. In these ways, the steeper, more marginal lands could support the needed livestock without having to sacrifice residue coverage on croplands. Additional competing demands for crop residues also exist—such as their use for cooking fuel and building material for thatched roofs and fencing. To meet these needs, fast-growing (preferably N fixing) trees can be planted in small woodlots or as field borders to provide the necessary fuel and building materials without harming—in fact often enhancing—soil quality. Such integration of trees into farming systems is known as *agroforestry*.

Agroforestry Systems

Agroforestry systems that integrate fast-growing, nitrogen-fixing woody species into small-scale farming systems show great promise in enhancing the supply and cycling of plant nutrients in the soil–plant system, while simultaneously increasing plant productivity and soil quality. We have already noted (see Section 13.8) the ability of deep-rooted, fast-growing trees to recycle nitrates that have leached to depths of several meters in some tropical soils. The nitrogen so salvaged (often as much as 100 kg N/ha) can be taken up by food crops when the tree residues are spread on the soil and decompose. This retrieved nitrogen represents a real input to the food-producing system, since otherwise the nitrogen would have been lost in the drainage waters.

The growth of fast-growing, nitrogen-fixing trees during the fallow period after the food crops have been harvested is another source of nitrogen for the production systems in subhumid areas (Table 20.13 and Figure 20.43). Nitrogen-fixation rates are equivalent to those provided by leguminous forages in the developed countries. When the legume foliage is added to the soil and allowed to decompose, some of the nitrogen is released for plant uptake. Part of

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Table 20.13
YIELD OF CORN IN KENYA FOLLOWING ONE OR TWO YEARS OF FALLOW IN WHICH VARIOUS SPECIES WERE GROWN
Three years of corn following two years of the nitrogen-fixing Sesbania tree produced more grain with less labor than the currently used systems (grass fallow and unfertilized corn).

Treatment	Corn grain yield, Mg/ha
2 years *Sesbania sesban*	5.4
Corn with fertilizer	4.0
1 year *Sesbania sesban*	3.4
Peanut–corn rotation	1.9
Grass fallow	1.8
Corn without fertilizer	1.1

From Kwesiga et al. (1997).

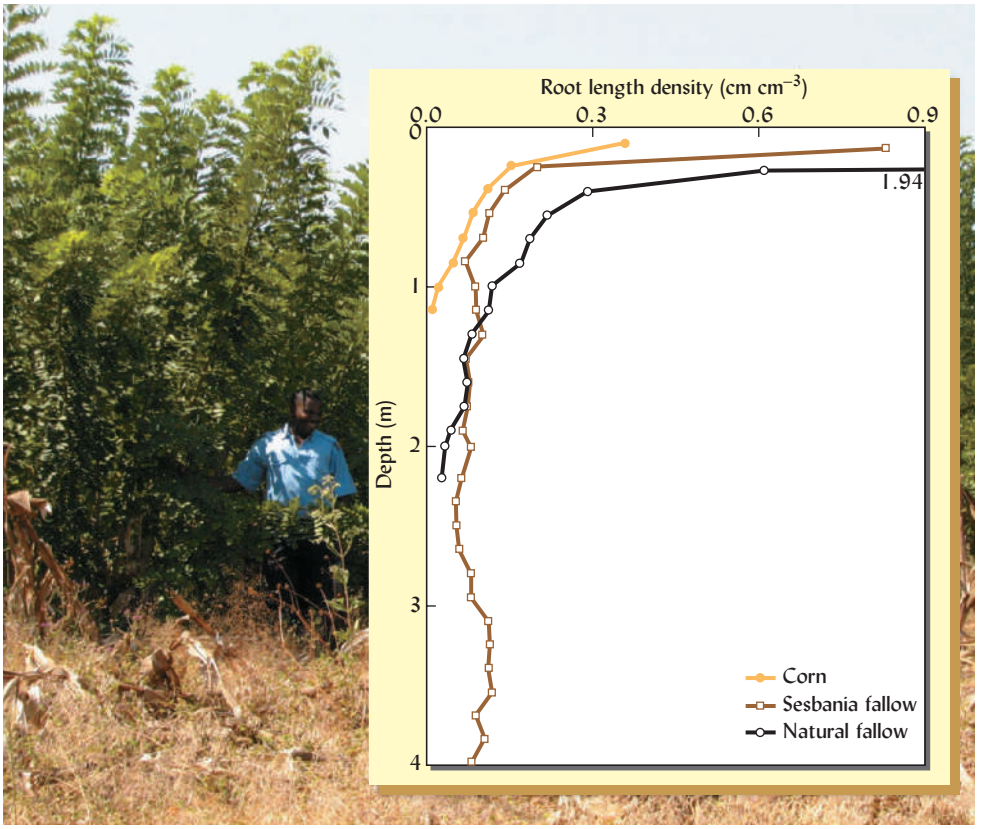

Figure 20.43 *Scientists and farmers have discovered the remarkably beneficial effects of including rapidly growing, nitrogen-fixing trees in rotations with food crops in Africa.* (Left) *The luxuriant growth of one such leguminous tree,* Gliricidia sepium, *one year after planting is shown in a field in western Tanzania.* (Right) *The very deep rooting system of another legume tree,* Sesbania sesban, *encourages the recycling of other nutrients as well as nitrogen. The remarkable yield response of corn* Sesbania sesban *is shown in Table 20.13.* [Photo courtesy Ray R. Weil; graph from Mekonnen et al. (1997), with permission of Kluwer Academic Publishers]

the N incorporated into labile forms of soil organic matter and into the microbial biomass will be available for later utilization by plants. Biological fixation is a significant source of nitrogen that must be more fully utilized.

Agroforestry Systems as Alternatives to Slash and Burn

There are several agroforestry systems that can provide viable alternatives to the destructive slash-and-burn methods in use today in Africa and elsewhere in the tropics. We will discuss two of these briefly.

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Mixed Tree Crops. First is the *mixed tree crop* system, in which the domesticated crop (often a tree species) is planted among existing native species (usually trees). In time, a number of the cultivated crop species may become dominant. The essential feature of the system, however, is that the soil will at no time be free of vegetation. Building on the experience of traditional systems, some scientists recommend the propagation of trees that produce high-valued products (fruits, nuts, and medicines) that can provide the producer with added income. The Kandy home gardens in Sri Lanka and the Telum forests of northeast Mexico are encouraging examples of successful systems developed by local people. The mixed tree crop system, which requires detailed knowledge of the species to be managed, offers economic returns while simultaneously assuring that soil quality will be maintained.

Alley Cropping. An agroforestry system known as *alley cropping* involves growing food crops in alleys, the borders of which are formed by fast-growing trees or shrubs, usually legumes. The hedgerows are pruned regularly to prevent shading of the food crop, and the prunings are used as mulch and as a source of nutrients for the food crop (see Figure 16.20). The mulch helps control weeds, prevents runoff and erosion, and reduces evaporation from the soil surface. Figure 20.44 (*left*) illustrates how the system works.

In areas with ample rainfall and moderately fertile soils, alley cropping systems have proven to be successful and crop yields can be maintained without having to leave the land fallow for years. The soil is protected from excess erosion and soil quality is improved (Table 20.14). But in other, quite infertile subhumid to semiarid areas, the hedgerow species compete with the food crops for nutrients and moisture, and yields suffer. Figure 20.44 (*right*) illustrates how competition reduces the effectiveness of alley cropping in drier regions and with more infertile soils. Thus, alley cropping may be beneficial in some cases, but is not a viable alternative to slash-and-burn in others.

Organic/Inorganic Combinations

In all parts of the world farmers and researchers are finding that by combining such organic materials as crop residues, agroforestry litter, animal wastes, and compost with

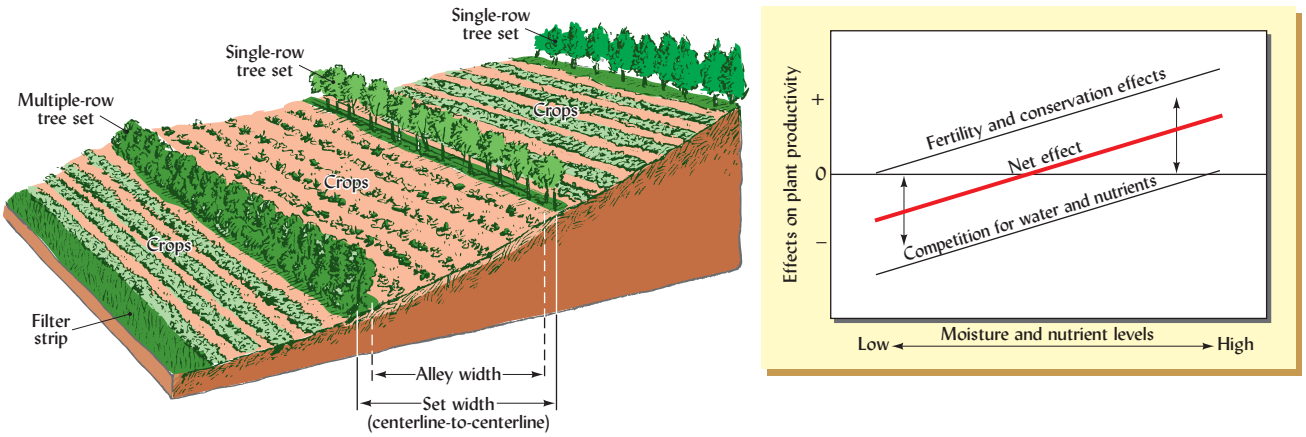

Figure 20.44 *In alley cropping annual crops are produced in between rows of fast-growing nitrogen-fixing trees.* (Left) *Before planting the cultivated crop, the trees are severely pruned to diminish their competitiveness and to supply an organic source of nutrients in the form of prunings that are spread over the cropped area. The prunings supply nutrients, organic matter, and protection from erosion. Such systems have shown some promise where the rainfall is sufficient for both the planted crop and the border trees, and where there is enough labor for cutting and spreading the tree trimmings.* (Right) *The upper line illustrates the positive nutrient cycling and soil conservation effects of alley cropping. The lower line shows the negative effects of competition for water and nutrients from the border row tree. The heavy center line indicates the net effect, which is generally positive in more humid areas with soils that have moderate plant nutrient levels. In drier, less-fertile areas, the competition for water and nutrients often results in a net reduction in crop yields.* (Diagram courtesy of USDA *(left)* and N. C. Brady *(right)*)

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Table 20.14
THE INFLUENCE OF CONSERVATION TILLAGE AND ALLEY CROPPING (WITH LEGUMINOUS TREE HEDGEROWS) ON RUNOFF AND SOIL EROSION LOSSES IN NIGERIA

	Runoff, % of rainfall		Soil erosion, Mg/ha	
System	Corn	Cowpeas	Corn	Cowpeas
Plow-till, no hedgerows	17.0	4.3	4.3	0.63
No-till, no hedgerows	1.3	0.8	0.1	0.03
Leucaena hedgerows	4.9	1.1	0.6	0.13
Gliricidia hedgerows	4.3	0.7	0.6	0.07

From Lal (1989).

modest levels of inorganic fertilizers, they can increase yields and simultaneously maintain or improve soil quality. The combination of organic materials and chemical fertilizers seems to provide a synergistic effect by which yield increases are greater from the combination than when the same inputs are supplied separately (Figure 20.45). Research shows that most African soils have a very low potential for sustainable agricultural use as they are managed today. In most cases, the replenishment of phosphorus in African soils will have to come primarily from inorganic sources, with supplementation from biological sources. In contrast, nitrogen replenishment can likely come primarily from biological sources such as leguminous plants, with inorganic sources providing the supplementation. The synergistic benefits from using combinations of organic and inorganic inputs may greatly enhance the quality of soils in Africa, Asia, Latin America, North America, or elsewhere in the world. The impacts of consistent amendment of soils with organic sources of nutrients, especially when some of the amendments are charred, can have very long lasting benefits (Box 20.4).

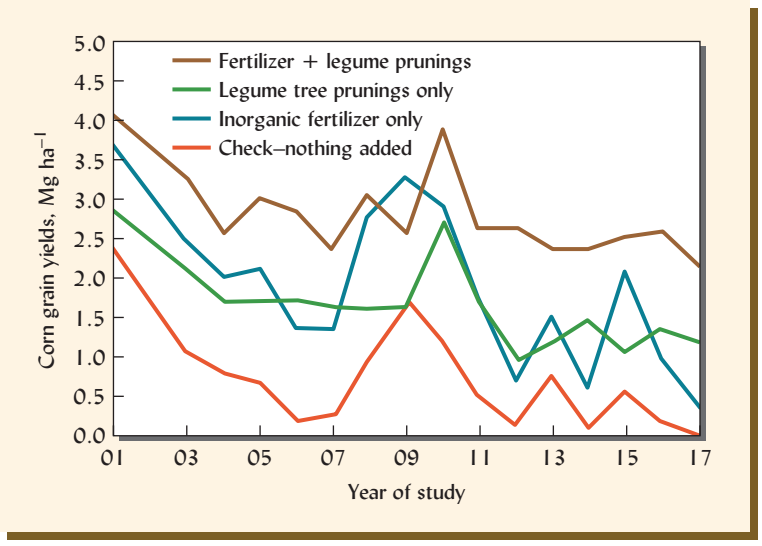

Figure 20.45 *Increased yields of corn grain from applications of legume tree prunings and inorganic fertilizers supplied separately and in combination during 17 years of cropping in humid southwestern Nigeria. The yield increases from plots receiving both organic and inorganic materials generally exceeded the yield increases from using either of the two materials separately. The beneficial effects of combined application of organic and inorganic materials were clearly demonstrated, especially in the later years.* [Graphed using data selected from Vanlauwe et al. (2012)]

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BOX 20.4

TERRA PRETA: ENDURING FERTILITY THAT CHARCOAL BUILT?[a]

In the Amazon basin, a region of highly weathered Oxisols and Ultisols, most soils are dominated by Fe and Al oxide clays, possess very low levels of fertility, and have little capacity to hold nutrients. So soil scientists exploring this region were both puzzled and astonished when they found small patches (averaging 20 ha) of dark colored, apparently highly fertile soils along the Amazon River and some of its major tributaries. Analyses indicated that the organic matter content of these soils was several times as great as that of the surrounding soils. Nutrient levels also proved to be much higher.

Isotope analyses indicated that most of the carbon in these soils accumulated several thousand years ago. It is believed that these patches of fertile soils were created by ancient peoples who once lived in small agricultural settlements carved out of the rainforest. Apparently they farmed these soils continuously for many centuries in such a manner that soil quality was greatly enhanced—rather than degraded—by agricultural use. Even today, some of these soils, which are called **Terra Preta** (*dark soil* in Portuguese), are dug up and sold locally for their high fertility.

Investigations have shown that Terra Preta soils are much higher in calcium and phosphorus than the surrounding soil because of amendment with large amounts of human excrement as well as with the bones of small animals eaten by the ancient farmers. But the really unique aspect of these soils is that much of the carbon in them is present as *charcoal*. Charcoal is produced by *charring* plant materials in smoldering, low temperature fires (as opposed to *burning* them in high temperature fires that leave only ash). The tiny bits of charcoal found in Terra Preta soils have a very porous structure that greatly aids in holding water and provides a very high capacity to retain nutrients in the form of dissolved organic compounds. A complex aromatic chemical structure makes the charcoal remarkably resistant to microbial breakdown. These properties of the charcoal result in very high and stable accumulations of carbon as well as high nutrient availability for plant growth (see also Section 20.9 on Biochar). In experimental plantings, crops grown in the Terra Preta soils have produced more than double the yield of those grown on nearby non-Terra Preta soils.

Soil scientists studying these unique human-influenced soils report that adding charcoal to soils may greatly improve soil quality and make soils resistant to degradation in agricultural use. Charcoal making produces an important fuel for people in the humid tropics (Figure 20.46) and can be sustainable if the wood required comes from forest plantations, rather than from the remaining natural forests. Waste bits of charcoal too small to sell for cooking fuel might provide a significant quantity of charcoal for soil amendment. Some researchers even suggest that charcoal could help reverse the degradation that soils now suffer under intensified "slash and burn" agriculture (see Section 20.7). To this end, they recommend developing what might be called a "slash and char" agriculture, in which the biomass from land clearing is smoldered rather than burned and soils are amended with food wastes and human and animal manure.

Figure 20.46 *Charcoal making is a cottage industry in much of Africa.* (Photo courtesy of Ray R. Weil)

[a]For an overview of Terra Preta soils and the potential of charcoal to enhance soil quality, see Glaser (2007).

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20.12 CONCLUSION

Soil scientists, in collaboration with colleagues in other disciplines, have developed the concept of *soil quality* to help quantify factors that are influencing the ability of the soil to function effectively in a variety of ecosystem roles. Although engineering uses are locally important, the primary measures of soil quality are enhanced plant productivity, waste recycling, and protection of environmental quality leading to human and animal health, and biological diversity. Human population pressures are forcing increased emphasis on the soil's function in enhancing plant productivity, but if soil quality is to be improved, we must simultaneously achieve the other goals as well.

Soil health describes the ability of the soil to self-regulate and function as a living system. Soil health incorporates the necessary chemical and physical soil properties, but emphasizes the resilience and effectiveness of the biological communities in soils. Soil health is promoted by plant and microbial diversity. Adding cover crops to many farming systems allows increases in this diversity that would not be possible if only crops for sale were grown.

Farmers of the world have performed near miracles in the past half century. They have increased food production at higher rates than at any time in history, more than matching the unprecedented increases in human population numbers. The increased food production has come primarily from intensification of agriculture on existing farmlands. While soil quality has been improved by some of the intensified systems, others have degraded soil, water, and atmospheric resources.

A major challenge facing humankind is the production of more food and fiber in the next 40–50 years than has been produced since the dawn of agriculture some 10,000 years ago. A new paradigm is needed to do this without degrading the environment, endangering human and animal health, or decreasing biological diversity. This paradigm envisages an ecosystem approach for farming—an approach that emphasizes the interaction of plant productivity with the productivity and well-being of all living organisms and with the quality of the environment. Organic farmers using many conservation practices will likely have a role to play in the new era focused on soil health and will be part of new, more effective farming systems for the resource-poor farmers of the world. A major lesson of the past few decades is that organic materials and nutrient cycling must not be forgotten even where inorganic fertilizers are needed to replenish nutrients lost by previous poor management. Much evidence suggests that combinations of organic and inorganic nutrients perform better than either alone. Biochars offer a unique way of managing the organic carbon cycle with potentially long-lasting benefits for soil quality and health. The world will look to partnerships among innovative scientists and farmers to apply sound science to the management of soil health and the enhanced provision of critical ecosystem services that benefit us all.

STUDY QUESTIONS

1. What is soil quality, how is it measured, and of what importance is it to all organisms that live in or on the soil?
2. Why is soil quality likely of greater societal concern today than it was 100 years ago?
3. Why does the biological productivity aspect of soil quality tend to receive more attention than do the aspects dealing with the environment and animal and human health? Is this comparative priority changing? Why?
4. Compare the provision of ecosystem services by soils in a mature forest; a mono-cropped, chemical-intensive vegetable farm; and a diverse, integrated vegetable, grain, and livestock farm.
5. What is meant by *soil resistance* and *soil resilience* as they relate to soil quality?
6. What technological inputs were largely responsible for the remarkable food- and fiber-production increases of the past three decades in the developing countries of Asia and Latin America? Will these inputs likely be significant in increasing food and fiber production in the next 30 years? Why or why not?
7. What are the positive and negative effects on soil quality of the intensive agricultural practices of the past half century?
8. How does the evolving ecosystem approach to plant production differ from the short-term economic return

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approach that has pertained in the past? Which approach will likely have a more positive effect on soil quality or health, and why?

9. What are some of the changes in nutrient management of intensified plant-production systems that are needed to improve soil productivity and agricultural sustainability and to enhance soil quality?
10. Africa is the only major region of the world where per-capita food production has declined in the past three decades. What are the reasons for this situation, and what major steps might be taken to change it?
11. What is *shifting cultivation*; why is its use today in many areas resulting in a decline in soil quality; and what are some promising alternatives?
12. In what areas of the world has the decline in soil quality been most extensive? Why has this decline taken place?
13. How can the proper integration of livestock with crop farming enhance soil quality in (a) developed-country intensive agriculture and (b) developing-country low-input agriculture?
14. If you are a local extension agent charged with helping farmers adopt the use of cover crops, what challenges do you think you would face from farmers and why? Do you think your organic farmers would be more or less likely to adopt the use of cover crops?
15. Explain the difference between biochar and ash. Would you choose to make biochar and use it? Why or why not.
16. As an organic farmer, you express adding fertility as feeding the soil. How does that phrase fit with the ideas underlying organic farming?

REFERENCES

AdeOluwa, O. O., and O. Cofie. 2012. "Urine as an alternative fertilizer in agriculture: Effects in amaranths (*Amaranthus caudatus*) production." *Renewable Agriculture and Food Systems* FirstView: 1–8.

Alexander, M. 1971. "Agriculture's responsibility in establishing soil quality criteria." *Environmental Improvement—Agriculture's Challenge in the Seventies*. National Academy of Sciences, Washington, D.C., pp. 66–71.

Andrews, S. S., D. L. Karlen, and C. A. Cambardella. 2004. "The soil management assessment framework: A quantitative soil quality evaluation method." *Soil Science Society of America Journal* **68**:1945–1962.

Ayaga, G., A. Todd, and P. C. Brookes. 2006. "Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-Saharan farming systems." *Soil Biology and Biochemistry* **38**:81–90.

Barański, M., D. Średnicka-Tober, N. Volakakis, C. Seal, R. Sanderson, G. B. Stewart, C. Benbrook, B. Biavati, E. Markellou, C. Giotis, J. Gromadzka-Ostrowska, E. Rembiałkowska, K. Skwarło-Sońta, R. Tahvonen, D. Janovská, U. Niggli, P. Nicot, and C. Leifert. 2014. "Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: A systematic literature review and meta-analyses." *British Journal of Nutrition* **112**:794–811.

Buresh, R. J., and P. A. Sanchez (eds.). 1997. *Replenishing Soil Fertility in Africa*. SSSA Special Publication No. 51. Soil Science Society of America, Madison, WI.

Cassman, K., S. Peng, D. Olk, J. Ladha, W. Reichardt, A. Dobermann, and U. Singh. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field crops research **56**:7-39.

Chemnitz, C., and J. Weigelt. 2015. *The Soil Atlas 2015*. Heinrich Böll Foundation, Institute for Advanced Sustainability Studies, Berlin and Potsdam, Germany. http://www.boell.de/sites/default/files/soil_atlas_2015.pdf.

Daily, G. C., T. Soderqvist, S. Aniyar, K. Arrow, P. Dasgupta, P. R. Ehrlich, C. Folke, A. Jansson, B.-O. Jansson, N. Kautsky, S. Levin, J. Lubchenco, K.-G. Maler, D. Simpson, D. Starrett, D. Tilman, and B. Walker. 2000. "The value of nature and the nature of value." *Science* **289**:395–396.

Doran, J. W., and A. J. Jones (eds.). 1996. *Methods for Assessing Soil Quality*. SSSA Special Publication No. 49. Soil Science Society of America, Madison, WI.

Drohan, P. J., and T. J. Farnham. 2006. "Protecting life's foundation: A proposal for recognizing rare and threatened soils." *Soil Science Society of America Journal* **70**:2086–2096.

Edgeworth, M., D. deB Richter, C. Waters, P. Haff, C. Neal, and S. J. Price. 2015. "Diachronous beginnings of the anthropocene: The lower bounding surface of anthropogenic deposits." *The Anthropocene Review*, **2**:33–58. .

Eigenberg, R. A., J. A. Nienaber, B. L. Woodbury, and R. B. Ferguson. 2006. "Soil conductivity as a measure of soil and crop status—A four-year summary." *Soil Science Society of America Journal* **70**:1600–1611.

Eswaran H., R. Almaraz, E. vanden Berg, and P. Reich. 1997. "An assessment of the soil resources of Africa in relation to productivity." *Geoderma* 77:1–18.

FAO. 2000. "Manual on integrated soil management and conservation practices," FAO Land and Water Bulletin No. 8. Food and Agriculture Organization of the United Nations, Rome, p. 215.

FAO. 2006b. FAOSTAT. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/ (verified 20 November 2006).

FAO. 2014. Faostat [Online]. Food and Agriculture Organization of the United Nations. Available at http://faostat.fao.org/ (verified 20 May 2014).

FOR REFERENCE PURPOSES ONLY

Girma, T. 2001. "Land degradation: A challenge to Ethiopia." *Environmental Management* **27**:815–824.

Glaser, B. 2007. "Prehistorically modified soils of central Amazonia: A model for sustainable agriculture in the twenty-first century." *Philosophical Transactions of the Royal Society B* **362**:187–196.

Gregorich, E. G., C. F. Drury, and J. A. Baldock. 2001. "Changes in soil carbon under long-term maize in monoculture and legume-based rotation." *Canadian Journal of Soil Science* **81**:21–31.

Gruver, J. B., and R. R. Weil. 2007. "Farmer perceptions of soil quality and their relationship to management-sensitive soil parameters." *Renewable Agriculture and Food Systems* **22**:271–281.

Heckman, J. R. 2006. "A history of organic farming: Transitions from Sir Albert Howard's war in the soil to USDA National Organic Program." *Renewable Agriculture and Food Systems* **21**:143–150.

Heckman, J. R. 2007. "Soil fertility in organic agriculture." *The Soil Profile* **17**:8. http://www.njaes.rutgers.edu/pubs/soilprofile/sp-v17.pdf.

Heinonen-Tanski, H., S. Pradhan, and P. Karinen. 2010. "Sustainable sanitation—A cost-effective tool to improve plant yields and the environment." *Sustainability* **2**:341–353.

Herrick, J. E., K. C. Urama, J. W. Karl, J. Boos, M.-V. V. Johnson, K. D. Shepherd, J. Hempel, B. T. Bestelmeyer, J. Davies, J. L. Guerra, C. Kosnik, D. W. Kimiti, A. L. Ekai, K. Muller, L. Norfleet, N. Ozor, T. Reinsch, J. Sarukhan, and L. T. West. 2013. "The global land-potential knowledge system (landPKS): Supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing." *Journal of Soil and Water Conservation* **68**:5A–12A.

Islam, K. R., and R. R. Weil. 2000. "Soil quality indicator properties in Mid-Atlantic soils as influenced by conservation management." *Journal of Soil and Water Conservation* **55**:69–78.

Kaisermann, A., A. Roguet, N. Nunan, P.-A. Maron, N. Ostle, and J.-C. Lata. 2013. "Agricultural management affects the response of soil bacterial community structure and respiration to water-stress." *Soil Biology and Biochemistry* **66**:69–77.

Karak, T., and P. Bhattacharyya. 2011. "Human urine as a source of alternative natural fertilizer in agriculture: A flight of fancy or an achievable reality." *Resources, Conservation and Recycling* **55**:400–408.

Karlen, D. L., E. G. Hurley, S. S. Andrews, C. A. Cambardella, D. W. Meek, M. D. Duffy, and A. P. Mallarino. 2006. "Crop rotation effects on soil quality at three northern corn/soybean belt locations." *Agronomy Journal* **98**:484–495.

Kavanagh, E. 2006. "Commentary letters—Looking at biofuels and bioenergy." *Science* **312**:1743–1749.

Klüpfel, L., M. Keiluweit, M. Kleber, and M. Sander. 2014. "Redox properties of plant biomass-derived black carbon (biochar)." *Environmental Science & Technology* **48**:5601–5611.

Kolby, E., and J. L. C. Jansen. 2003. "Urine can be used as fertiliser [Online]." Wastewater and Water Supply Division, Danish EPA. Available at http://www.mst.dk/project/NyViden/2001/11040000.htm (posted 28 July 2003; verified 15 July 2006).

Kuppusamy, S., P. Thavamani, M. Megharaj, K. Venkateswarlu, and R. Naidu. 2016. "Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions." *Environment International* **87**:1–12.

Kwesiga, F. R., S. Franzel, F. Place, D. Phiri, and C. P. Simwanza. 1997. "Sesbania improved fallows in Eastern Zambia: Their inception, development and farmer enthusiasm." In R. J. Buresh and P. J. Cooper (eds.). *The Science and Practice of Short Term Improved Fallows*. Kluwer Academic Publishers, Dordrecht, Netherlands.

Lal, R. 1989. "Agroforestry systems and soil surface management of a tropical Alfisol: II: Water runoff, erosion and nutrient loss." *Agroforestry Systems* **8**:97–111.

Lal, R. 2006. "Managing soils for feeding a global population of 10 billion." *Journal of the Science of Food and Agriculture* **86**:2273–2284.

Lehmann, J. 2007. "Bio-energy in the black." *Frontiers in Ecology and the Environment* **5**:381–387.

Lehman, R., C. Cambardella, D. Stott, V. Acosta-Martinez, D. Manter, J. Buyer, J. Maul, J. Smith, H. Collins, J. Halvorson, R. Kremer, J. Lundgren, T. Ducey, V. Jin, and D. Karlen. 2015a. "Understanding and enhancing soil biological health: The solution for reversing soil degradation." *Sustainability* **7**:988–1027.

Lehman, R. M., V. Acosta-Martinez, J. S. Buyer, C. A. Cambardella, H. P. Collins, T. F. Ducey, J. J. Halvorson, V. L. Jin, J. M. F. Johnson, R. J. Kremer, J. G. Lundgren, D. K. Manter, J. E. Maul, J. L. Smith, and D. E. Stott. 2015b. "Soil biology for resilient, healthy soil." *Journal of Soil and Water Conservation* **70**:12A–18A.

Liebig, M. A., and J. W. Doran. 1999. "Impact of organic production practices on soil quality indicators." *Journal of Environmental Quality* **28**:1601–1609.

Lounsbury, N. P., and R. R. Weil. 2015. "No-till seeded spinach after winterkilled cover crops in an organic production system." *Renewable Agriculture and Food Systems* **30**:1–13(in press).

Mekonnen, K., R. S. Buresh, and B. Jama. 1997. "Root and inorganic nitrogen distributions in Sesbania fallow, natural fallow and maize fields." *Plant and Soil* **188**:319–327.

Miguez, F. E., and G. A. Bollero. 2005. "Review of corn yield response under winter cover cropping systems using meta-analytic methods." *Crop Science* **45**:2318–2329.

Oldeman, L. R., R. T. A. Hakkeling, and W. G. Sombroek. 1990. *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*. ISRIC, Wageningen, Netherlands; UNEP, Kenya.

FOR REFERENCE PURPOSES ONLY

Olson, K., S. A. Ebelhar, and J. M. Lang. 2014. "Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration." *Open Journal of Soil Science* 4:284–292.

Pradhan, S. K., A.-M. Nerg, A. Sjöblom, J. K. Holopainen, and H. Heinonen-Tanski. 2007. "Use of human urine fertilizer in cultivation of cabbage (*Brassica oleracea*)—Impacts on chemical, microbial, and flavor quality." *Journal of Agricultural and Food Chemistry* 55:8657–8663.

Ragauskas, A. J., C. K. Williams, B. H. Davison, G. Britovsek, J. Cairney, C. A. Eckert, W. J. Frederick, Jr., J. P. Hallett, D. J. Leak, C. L. Liotta, J. R. Mielenz, R. Murphy, R. Templer, and T. Tschaplinski. 2006. "The path forward for biofuels and biomaterials." *Science* 311:484–489.

Ray, D. K., N. D. Mueller, P. C. West, and J. A. Foley. 2013. "Yield trends are insufficient to double global crop production by 2050." *PloS One* 8:e66428.

Reganold, J. P., J. D. Glover, P. K. Andrews, and H. R. Hinman. 2001. "Sustainability of three apple production systems." *Nature* 410:927–930.

Reganold, J.P., and J.M. Wachter. 2016. "Organic agriculture in the twenty-first century". *Nature Plants* 2:15221.

Richert, A., R. Gensch, H. Jönsson, T.-A. Stenström, and L. Dagerskog. 2010. "Practical guidance on the use of urine in crop production," EcoSanRes Series 2010-1. EcoSanRes Programme, Stockholm Environment Institute, Stockholm. http://sei-international.org/mediamanager/documents/Publications/Air-land-water-resources/ecosan-urine-in-crops-100824%20web.pdf.

Sanchez, P. A., and M. S. Swaminathan. 2005. "Hunger in Africa: The link between unhealthy people and unhealthy soils." *Lancet* 365:442–444.

Sanchez, P. A., and T. J. Logan. 1992. "Myths and science about the chemistry and fertility of soils of the tropics." In P. A. Sanchez and R. Lal (eds.). *Myths and Science of Soils of the Tropics*. SSSA Special Publication No. 29. Soil Science Society of America, Madison WI, pp. 35–46.

Seufert, V., N. Ramankutty, and J. A. Foley. 2012. "Comparing the yields of organic and conventional agriculture." *Nature* 485:229–232.

Seybold, C. A., J. E. Herrick, and J. J. Brejda. 1999. "Soil resilience: A fundamental component of soil quality." *Soil Science* 164:224–234.

Shrestha, D., A. Srivastava, S. M. Shakya, J. Khadka, and B. S. Acharya. 2013. "Use of compost supplemented human urine in sweet pepper (*Capsicum annuum* L.) production." *Scientia Horticulturae* 153:8–12.

Shukla, M. K., R. Lal, and M. Ebinger. 2006. "Determining soil quality indicators by factor analysis." *Soil Tillage Research* 87:194–204.

Singh, R., J. N. Babu, R. Kumar, P. Srivastava, P. Singh, and A. S. Raghubanshi. 2015. "Multifaceted application of crop residue biochar as a tool for sustainable agriculture: An ecological perspective." *Ecological Engineering* 77:324–347.

Stoorvogel, J. J., E. M. A. Smaling, and B. H. Janssen. 1993. "Calculating soil nutrient balances in Africa at different scales." *Fertilizer Research* 35:227–235.

Tully, K., C. Sullivan, R. Weil, and P. Sanchez. 2015. "The state of soil degradation in sub-Saharan Africa: Baselines, trajectories, and solutions." *Sustainability* 7:6523–6552.

United Nations Secretariat. 2007. "World population prospects: The 2006 revision." Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. http://esa.un.org//unpp (verified 27 April 2007).

USDA/AMS. 2006. "The organic foods productioné act of 1990-regulatory text." USDA Agricultural Marketing Service. http://www.ams.usda.gov/nop/NOP/standards/FullRegTextOnly.html.

Vanlauwe, B., G. Nziguheba, O. C. Nwoke, J. Diels, N. Sanginga, R. Merckx, A. Bationo, B. Waswa, J. Kihara, I. Adolwa, B. Vanlauwe, and K. Saidou. 2012. *Long-Term Integrated Soil Fertility Management in South-Western Nigeria: Crop Performance and Impact on the Soil Fertility Status, Lessons Learned from Long-Term Soil Fertility Management Experiments in Africa*. Springer, Netherlands, pp. 175–200.

Veum, K., K. Goyne, R. Kremer, R. Miles, and K. Sudduth. 2014. "Biological indicators of soil quality and soil organic matter characteristics in an agricultural management continuum." *Biogeochemistry* 117:81–99.

Weil, R. R., K. R. Islam, M. A. Stine, J. B. Gruver, and S. E. Samson-Liebig. 2003. "Estimating active carbon for soil quality assessment: A simplified method for lab and field use." *American Journal of Alternative Agriculture* 18:3–17.

Wilsenach, J. A. 2006. "Treatment of source separated urine and its effects on wastewater systems." Ph.D. dissertation, Delft University of Technology, Delft.

Wingeyer, A. B., T. J. Amado, M. Pérez-Bidegain, G. A. Studdert, C. H. P. Varela, F. O. Garcia, and D. L. Karlen. 2015. "Soil quality impacts of current South American agricultural practices." *Sustainability* 7:2213–2242.

Winter, C. K., and S. F. Davis. 2007. "Are organic foods healthier? Industry perspectives." *Crops Soils Agronomy News* 52:2–13. Available online at https://www.soils.org/news.html.

Xie, T., K. R. Reddy, C. Wang, E. Yargicoglu, and K. Spokas. 2014. "Characteristics and applications of biochar for environmental remediation: A review." *Critical Reviews in Environmental Science and Technology* 45:939–969.

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Appendix A

World Reference Base, Canadian, and Australian Soil Classification Systems

Table A.1
Soil Reference Groups in the World Reference Base (WRB) for Soil Resources[a]
The World Reference Base provides a global vocabulary for communicating about different kinds of soils and a reference by which various national soil classification systems (such as U.S. Soil Taxonomy and the Canadian Soil Classification System discussed in this text) can be compared and correlated. The 32 Reference Soil Groups are differentiated mainly according to the primary pedogenesis process that has produced the characteristic soil features, except where "special" soil parent materials are of overriding importance. Each Reference Soil Group can be subdivided using a unique list of possible prefix and suffix qualifiers (not shown here[b]). These qualifiers indicate secondary soil-forming processes that significantly affected the primary soil characteristics especially important to soil use. To avoid making the classification of soils dependent on the availability of climatic data, separations are not based on specific climatic characteristics (as is the case in U.S. Soil Taxonomy).

Reference Soil Group[c]	Major Soil Characteristics	Approximate Equivalents in U.S. Soil Taxonomy[d]
	Organic Soils	
Histosols (HS)	Composed of organic materials	Most Histosols and Histels
	Mineral Soils Dominantly Influenced by Human Activity	
Anthrosols (AT)	Soils with long and intensive agriculture use	Anthropic and Plaggic subgroups
Technosols (TC)	Soils containing many artifacts	Subgroups, mainly of Entisols, with Anthraltic, Anthroportic, or Anthropic adjectives.
	Soils with Limited Rooting Due to Shallow Permafrost or Stoniness	
Cryosols (CR)	Ice-affected soils: Cryosols	Gelisols
Leptosols (LP)	Shallow or extremely gravelly soils	Lithic subgroups of Inceptisols and Entisols
	Soils Influenced by Water	
Vertisols (VR)	Alternating wet-dry conditions, rich in swelling clays	Vertisols
Fluvisols (FL)	Young soils in alluvial deposits	Fluvents and Fluvaquents
Solonchaks (SC)	Strongly saline soils	Salids and salic or halic great groups of other orders
Solonetz (SN)	Soils with subsurface clay accumulation, rich in sodium	Natric great groups of Alfisols, Aridisols, and Mollisols
Gleysols (GL)	Groundwater-affected soils	Endoaquic great groups (e.g., Endoaqualfs, Endoaquolls, Endoaquults, Endoaquents, Endoaquepts)
	Soils for Which Aluminium (Al) Chemistry Plays a Major Role in Their Formation	
Andosols (AN)	Young soils from volcanic ash and tuff deposits	Andisols
Podzols (PZ)	Acid soils with a subsurface accumulation of iron–aluminium–organic compounds	Spodosols

(continued)

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Table A.1 (CONTINUED)

Reference Soil Group[c]	Major Soil Characteristics	Approximate Equivalents in U.S. Soil Taxonomy[d]
Plinthosols (PT)	Wet soils with an irreversibly hardening mixture of iron, clay, and quartz in the subsoil	Plinthic great groups of Aqualfs, Aquox, and Ultisols
Nitisols (NT)	Deep, dark red, brown, or yellow clayey soils having a pronounced shiny, nut-shaped structure	Parasesquic Inceptisols and some Oxisols and Ultisols
Ferralsols (FR)	Deep, strongly weathered soils with a chemically poor, but physically stable subsoil	Oxisols
	Soils with Stagnant Water	
Planosols (PL)	Soils with a bleached, temporarily water-saturated topsoil on a slowly permeable subsoil	Albaqualfs and Albaquults and some albaquic subgroups of Alfisols and Ultisols
Stagnosols (ST)	Soil with temporarily water-saturated topsoil on structural or moderate textural discontinuity	Epiaquic and Anthraquic great groups
	Mineral Soils with Humus-Rich Topsoils and a High Base Saturation Typically in Grasslands	
Chernozems (CH)	Soils with a thick, dark topsoil, rich in organic matter with a calcareous subsoil	Calciudolls
Kastanozems (KS)	Soils with a thick, dark brown topsoil, rich in organic matter and a calcareous or gypsum-rich subsoil	Many Calciustolls and Calcixerolls
Phaeozems (PH)	Soils with a thick, dark topsoil, rich in organic matter and evidence of removal of carbonates	Many Cryolls, Udolls, and Albolls
	Soils with Accumulation of Nonsaline Substances and Influenced by Aridity	
Gypsisols (GY)	Soils with accumulation of secondary gypsum	Gypsids and some gypsic great groups of other orders
Durisols (DU)	Soils with accumulation of secondary silica	Durids and some Duric great groups of other orders
Calcisols (CL)	Soils with accumulation of secondary calcium carbonates	Calcids and Calcic great groups of Inceptisols
	Mineral Soils with a Clay-Enriched Subsoil	
Albeluvisols (AB)	Acid soils with a bleached horizon penetrating into a clay-rich subsurface horizon	Some Glossudalfs
Alisols (AL)	Soils with subsurface accumulation of high activity clays, and low base saturation	Ultisols and ultic Alfisols
Acrisols (AC)	Soils with subsurface accumulation of low activity clays and low base saturation	Kandic great groups of Alfisols and Ultisols
Luvisols (LV)	Soils with subsurface accumulation of high activity clays and high base saturation	Haplo and pale great groups of Alfisols
Lixisols (LX)	Soils with subsurface accumulation of low activity clays and high base saturation	Kandic great groups of Alfisols with high base saturation
	Relatively Young Soils or Soils with Little or No Profile Development	
Umbrisols (UM)	Acid soils with a thick, dark topsoil, rich in organic matter	Many Umbric great groups of Inceptisols
Arenosols (AR)	Very sandy soils featuring no or only very weak B horizon development	Psamments, grossarenic subgroups of other orders
Cambisols (CM)	Soil with only weakly to moderately developed B horizons	Cambids and many Inceptisols
Regosols (RG)	Soils with very limited soil development, often shallow to rock	Orthents, some Psamments and other Entisols

[a]Based on FAO (2006). World reference base for soil resources 2006: A framework for international classification correlation and communication. World Soil Resources Reports 103. Food and Agriculture Organization of the United Nations and United Nations Environmental Program, Rome. 128 pp. and on personal communication from Bob Engel (USDA/NRCS) and Michéli Erika (Univ. Agric. Sci., Hungary).

[b]As one example, the Kastanozems reference group can be subdivided using the prefix modifiers Vertic, Gypsic, Calcic, Luvic, Hyposodic, Siltic, Chromic, Anthric, and Haplic.

[c]Abbreviations (often used as symbols on soil maps) in parentheses.

[d]As discussed in Chapter 3 of this text.

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Table A.2
The Australian Soil Classification System and Approximate Correlations with U.S. Soil Taxonomy

Order	Main Characteristics	Soil Taxonomy Order and Suborders
Anthroposols	"Man-made" soils	Anthraltic, Anthroportic or Antrhopic subgroups
Calcarosols	B horizon calcareous and lacking a marked clay accumulation	Aridisols, Alfisols (Ustalfs, Xeralfs)
Chromosols	Strong clay accumulation and pH > 5.5 in B horizon	Alfisols, some Aridisols
Dermosols	B horizon well structured but lacking a marked clay accumulation	Mollisols, Alfisols, Ultisols
Ferrosols	B horizon high in Fe and lacking a marked clay accumulation, without vertic properties.	Oxisols, some Alfisols
Hydrosols	Prolonged seasonal water saturation	Aquic subgroups of Alfisols, Ultisols, Inceptisols, salic Aridisols, and some Histosols
Kandosols	B horizon massive or lacking strong structure, and lacking a marked clay accumulation	Alfisols, Ultisols, and Aridisols with massive B horizon structure
Kurosols	Strong clay accumulation and pH < 5.5 in B horizon; clear or abrupt B horizon boundary.	Ultisols, some Alfisols
Organosols	Organic materials; not regularly inundated by saline tidal waters.	Histosols
Podosols	Acid soils with subsurface accumulation of Fe, Al-organic compounds	Spodosols, some Entisols
Rudosols	Negligible (rudimentary) horizon differentiation	Entisols, salic Aridisols
Sodosols	Strong clay accumulation in B horizon, with high sodium saturation	Natric subgroups of Alfisols, Aridisols
Tenosols	Weak horizon differentiation	Inceptisols, Aridisols, Entisols
Vertosols	High clay (>35%), deep cracks, slickensides	Vertisols

Modified from: CSIRO Land and Water (2016). http://www.clw.csiro.au/aclep/asc_re_on_line_V2/soilhome.htm

Table A.3
Summary with Brief Descriptions of the Soil Orders in the Soil Classification System of Canada

The Canadian Soil Classification System is one of many national soil classification systems used in various countries around the world. Of these, it is perhaps the most closely aligned with the U.S. Soil Taxonomy. It includes five hierarchical categories: order, great group, subgroup, family, and series. The system is designed to apply principally to the soils of Canada. The soil orders of the Canadian System of Soil Classification are described in this Table and soil orders and some great groups are compared to the U.S. Soil Taxonomy in Table A.4.

Brunisolic	Soils with sufficient development to exclude them from the Regosolic order, but lacking the degree or kind of horizon development specified for other soil orders.
Chernozemic	Soils with high base saturation and surface horizons darkened by the accumulation of organic matter from the decomposition of plants from grassland or grassland-forest ecosystems.
Cryosolic	Soils formed in either mineral or organic materials that have permafrost either within 1 m of the surface or within 2 m if more than one-third of the pedon has been strongly cryoturbated, as indicated by disrupted, mixed, or broken horizons.

(continued)

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Table A.3 (CONTINUED)

Gleysolic	Gleysolic soils have features indicative of periodic or prolonged saturation (i.e., gleying, mottling) with water and reducing conditions.
Luvisolic	Soils with light-colored, eluvial horizons that have illuvial B horizons in which silicate clay has accumulated.
Organic	Organic soils developed on well- to undecomposed peat or leaf litter.
Podzolic	Soils with a B horizon in which the dominant accumulation product is amorphous material composed mainly of humified organic matter combined in varying degrees with Al and Fe.
Regosolic	Weakly developed soils that lack development of genetic horizons.
Solonetzic	Soils that occur on saline (often high in sodium) parent materials, which have B horizons that are very hard when dry and swell to a sticky mass of very low permeability when wet. Typically the solonetzic B horizon has prismatic or columnar macrostructure that breaks to hard to extremely hard, blocky peds with dark coatings.
Vertisolic	Soils with high contents of expanding clays that have large cracks during the dry parts of the year and show evidence of swelling, such as gilgae and slickensides.

Table A.4
COMPARISON OF U.S. SOIL TAXONOMY AND THE CANADIAN SOIL CLASSIFICATION SYSTEM
Note that because the boundary criteria differ between the two systems, certain U.S. Soil Taxonomy soil orders have equivalent members in more than one Canadian Soil Classification System soil order.[a]

U.S. Soil Taxonomy Soil Order	Canadian System Soil Order	Canadian System Great Group	Equivalent Lower-Level Taxa in U.S. Soil Taxonomy
Alfisols	Luvisolic	Gray Brown Luvisols	Hapludalfs
		Gray Luvisols	Haplocryalfs, Eutrocryalfs, Fragudalfs, Glossocryalfs, Palecryalfs, and some subgroups of Ustalfs and Udalfs
	Solonetzic	Solonetz	Natrudalfs and Natrustalfs
		Solod	Glossic subgroups of Natraqualfs, Natrudalfs, and Natrustalfs
Andisols	Components of Brunisolic and Cryosolic		
Aridisols	Solonetzic		Frigid families of Natrargids
Entisols	Regosolic		Cryic great groups and frigid families of Entisols, except Aquents
		Regosol	Cryic great groups and frigid families of Folists, Fluvents, Orthents, and Psamments
Gelisols	Cryosolic	Turbic Cryosol	Turbels
		Organic Cryosol	Histels
		Stagnic Cryosol	Orthels
Histosols	Organic	Fibrisol	Cryofibrists, Sphagnofibrists
		Mesisol	Cryohemists
		Humisol	Cryosaprists
Inceptisols	Brunisolic	Melanic Brunisol	Some Eutrustepts
		Eutric Brunisol	Subgroups of Cryepts; frigid and mesic families of Haplustepts
		Sombric Brunisol	Frigid and mesic families of Udepts, and Ustept and Humic Dystrudepts
		Dystric Brunisol	Frigid families of Dystrudepts and Dystrocryepts

(continued)

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Table A.4 (Continued)

U.S. Soil Taxonomy Soil Order	Canadian System Soil Order	Canadian System Great Group	Equivalent Lower-Level Taxa in U.S. Soil Taxonomy
	Gleysolic		Cryic subgroups and frigid families of Aqualfs, Aquolls, Aquepts, Aquents, and Aquods
		Humic Gleysol	Humaquepts
		Gleysol	Cryaquepts and frigid families of Fragaquepts, Epiaquepts, and Endoaquepts
Mollisols	Chernozemic	Brown	Xeric and Ustic subgroups of Argicryolls and Haplocryolls
		Dark Brown	Subgroups of Argicryolls and Haplocryolls
		Black	Typic subgroups of Argicryolls and Haplocryolls
		Dark Gray	Alfic subgroups of Argicryolls
	Solonetzic	Solonetz	Natricryolls and frigid families of Natraquolls and Natralbolls
		Solod	Glossic subgroups of Natricryolls
Oxisols	Not relevant in Canada		
Spodosols	Podzolic	Humic Podzol	Humicryods, Humic Placocryods, Placohumods, and frigid families of other Humods
		Ferro-Humic Podzol	Humic Haplocryods, some Placorthods, and frigid families of humic subgroups of other Orthods
		Humo-Ferric Podzol	Haplorthods, Placorthods, and frigid families of other Orthods and Cryods except humic subgroups
Ultisols	Not relevant in Canada		
Vertisols	Vertisolic	Vertisol	Haplocryerts
		Humic Vertisol	Humicryerts

[a]Based on information in Soil Classification Working Group, 1998, *The Canadian System of Soil Classification*, 3rd ed. (Ottawa: Agriculture and Agri-Food Canada). Publication No. A53-1646/1997E. http://sis.agr.gc.ca/cansis/taxa/cssc3/index.html

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Appendix B

SI Units, Conversion Factors, Periodic Table of the Elements, and Plant Names

Basic SI Units of Measurement

Parameter	Basic Unit	Symbol
Amount of substance	mole	mol
Electrical current	ampere	A
Length	meter	m
Luminous intensity	candela	cd
Mass	gram (kilogram)	g (kg)
Temperature	kelvin	K
Time	second	s

Prefixes Used to Indicate Order of Magnitude

Prefix	Multiple	Abbreviation	Multiplication Factor
exa	10^{18}	E	1,000,000,000,000,000,000
peta	10^{15}	P	1,000,000,000,000,000
tera	10^{12}	T	1,000,000,000,000
giga	10^{9}	G	1,000,000,000
mega	10^{6}	M	1,000,000
kilo	10^{3}	k	1,000
hecto	10^{2}	h	100
deca	10	da	10
deci	10^{-1}	d	0.1
centi	10^{-2}	c	0.01
milli	10^{-3}	m	0.001
micro	10^{-6}	μ	0.000 001
nano	10^{-9}	n	0.000 000 001
pico	10^{-12}	p	0.000 000 000 001
femto	10^{-15}	f	0.000 000 000 000 001
atto	10^{-18}	A	0.000 000 000 000 000 001

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Factors for Converting Non-SI Units to SI Units

Non-SI Unit	Multiply by[a]	To Obtain SI Unit
	Length	
inch, in.	2.54	centimeters, cm (10^{-2} m)
foot, ft	0.304	meter, m
mile,	1.609	kilometer, km (10^{3} m)
micron, μ	1.0	micrometer, μm (10^{-6} m)
Ångstrom unit, Å	0.1	nanometer, nm (10^{-9} m)
	Area	
acre, ac	0.405	hectare, ha (10^{4} m^2)
square foot, ft^2	9.29×10^{-2}	square meter, m^2
square inch, in^2	645	square millimeter, mm^2
square mile, mi^2	2.59	square kilometer, km^2
	Volume	
bushel, bu	35.24	liter, L
cubic foot, ft^3	2.83×10^{-2}	cubic meter, m^3
cubic inch, $in.^3$	1.64×10^{-5}	cubic meter, m^3
gallon (U.S.), gal	3.78	liter, L
quart, qt	0.946	liter, L
acre-foot, ac-ft	12.33	hectare-centimeter, ha-cm
acre-inch, ac-in.	1.03×10^{-2}	hectare-meters, ha-m
ounce (fluid), oz	2.96×10^{-2}	liter, L
pint, pt	0.473	liter, L
	Mass	
ounce (avdp), oz	28.4	gram, g
pound, lb	0.454	kilogram, kg (10^{3} g)
ton (2000 lb)	0.907	megagram, Mg (10^{6} g)
tonne (metric), t	1000	kilogram, kg
	Radioactivity	
curie, Ci	3.7×10^{10}	becquerel, Bq
picocurie per gram, pCi/g	37	becquerel per kilogram, Bq/kg
	Yield and Rate	
pound per acre, lb/ac	1.121	kilogram per hectare, kg/ha
pounds per 1000 ft^2	48.8	kilogram per hectare, kg/ha
bushel per acre (60 lb), bu/ac	67.19	kilogram per hectare, kg/ha
bushel per acre (56 lb), bu/ac	62.71	kilogram per hectare, kg/ha
bushel per acre (48 lb), bu/ac	53.75	kilogram per hectare, kg/ha
gallon per acre (U.S.), gal/ac	9.35	liter per hectare, L/ha
ton (2000 lb) per acre	2.24	megagram per hectare, Mg/ha
miles per hour, mph	0.447	meter per second, m/s
gallon per minute (U.S.), gpm	0.227	cubic meter per hour, m^3/h
cubic feet per second, cfs	101.9	cubic meter per hour, m^3/h
	Pressure	
atmosphere, atm	0.101	megapascal, MPa (10^{6} Pa)
bar	0.1	megapascal, MPa
pound per square foot, lb/ft^2	47.9	pascal, Pa
pound per square inch, lb/in^2	6.9×10^{3}	pascal, Pa
	Temperature	
degrees Fahrenheit (°F – 32)	0.556	degrees, °C
degrees Celsius (°C + 273)	1	Kelvin, K
	Energy	
British thermal unit, Btu	1.05×10^{3}	joule, J
calorie, cal	4.19	joule, J
dyne, dyn	10^{-5}	newton, N
erg	10^{-7}	joule, J
foot-pound, ft-lb	1.36	joule, J
	Concentrations	
percent, %	10	gram per kilogram, g/kg
part per million, ppm	1	milligram per kilogram, mg/kg
milliequivalents per 100 grams	1	centimole per kilogram, cmol/kg

[a]To convert from SI to non-SI units, *divide* by the factor given.

FOR REFERENCE PURPOSES ONLY

Periodic Table of the Elements with Notes Concerning Relevance to Soil Science

Based on atomic mass of $^{12}C = 12.0$. Numbers in parentheses are the mass numbers of the most stable isotopes of radioactive elements.

Group IA	Group IIA	Group IIIB	Group IVB	Group VB	Group VIB	Group VIIB	Group VIIIB	Group VIIIB	Group VIIIB	Group IB	Group IIB	Group IIIA	Group IVA	Group VA	Group VIA	Group VIIA	Group VIIIA
1 H 1.01 Hydrogen																	2 He 4.00 Helium
3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
11 Na 22.99 Sodium	12 Mg 24.30 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.88 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.69 Nickel	29 Cu 63.55 Copper	30 Zn 65.38 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
55 Cs 132.91 Cesium	56 Ba 137.33 Barium	57 La 138.91 Lanthanum	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.21 Rhenium	76 Os 190.2 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra (226) Radium	89 Ac (227) Actinium	104 Unq (261) Unnilquadium	105 Unp (262) Unnilpentium	106 Unh (263) Unnilhexium	107 Uns (262) Unnilseptium	108 Uno (265) Unniloctium										

Metals ← → Nonmetals

58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.36 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
90 Th (232) Thorium	91 Pa (231) Protactinium	92 U (238) Uranium	93 Np (237) Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (260) Lawrencium

Atomic number
Symbol
Atomic mass
87 Fr (223) Francium

Elements known to be nutrients for animals or plants. Some are also toxic in excessive amounts.

Elements toxic to organisms in small amounts, and not known to serve as nutrients.

Other elements commonly studied in Soil Science because of soil-environmental impacts or because of their use as tracers or electrodes. (Br is used to trace anionic solutes such as nitrate. Isotopes of Rb and Sr are used to trace K and Ca in plants and soils. Cs and Ti are used to trace geological processes such as soil erosion. Pt and Ag are used in electrodes for measuring soil redox potential and pH, respectively.)

These 22 elements are needed as essential mineral nutrients by humans: macronutrients (calcium, chloride, magnesium, phosphorus, potassium, sodium, and sulfur) and micronutrients (chromium, cobalt, copper, fluoride, iodine, iron, manganese, molybdenum, nickel, selenium, silicon, tin, vanadium, zinc).

FOR REFERENCE PURPOSES ONLY

Plants Mentioned in This Text: Their Common and Scientific Names

acacia, apple ring	*Faidherbia albida* (Del.) A. Chev. [syn. *Acacia albida*]
acacia, catclaw	*Acacia greggii* Gray
alder	*Alnus spp.* P. Mill.
alder, red	*Alnus rubra* Bong.
alfalfa	*Medicago sativa* L.
alkali grass, Nutall's	*Puccinellia nuttalliana* (J.A. Schultes) A.S. Hitchc.
alkali sacaton	*Sporobolus airoides* (Torr.) Torr.
almond	*Prunus dulcis* (P. Mill.) D.A. Webber
andromeda (bog rosemary)	*Andromeda polifolia* L.
apple	*Malus spp.* P. Mill.
apricot	*Prunus armeniaca* L.
arborvitae	*Thuja occidentalis* L.
ash	*Fraxinus spp.* L.
ash, white	*Fraxinus americana* L.
asparagus	*Asparagus officinalis.* L.
aspen	*Populus spp.* L.
aspen, quaking	*Populus tremuloides* Michx.
autumn olive	*Elaeagnus umbellata* Thunb.
azalea	*Rhododendron spp.* L.
azolla	*Azolla spp.* L.
bahia grass	*Paspalum notatum* Flueggé
banana	*Musa acuminata* Colla
barley, forage	*Hordeum vulgare* L.
bean, broad (faba)	*Vicia faba* L.
bean, common	*Phaseolus vulgaris* L.
bean, winged	*Psophocarpus tetragonobus* L. D.C.
beech, American	*Fagus grandifolia* Ehrh.
beet, garden	*Beta procumbens* L.
beet, sugar	*Beta vulgaris* L.
bentgrass	*Agrostis stolonifera* L.
bermudagrass	*Cynodon dactylon* (L.) Pers.
birch	*Betula spp.* L.
birch, black	*Betula lenta* L.
black cherry	*Prunus serotina* Ehrh.
black locust	*Robinia pseudoacacia* L.
blackberry	*Rubus spp.* L.
blueberry	*Vaccinium spp.* L.
bluegrass, Kentucky	*Poa pratensis* L. ssp. *pratensis*
bog rosemary	*Andromeda polifolia* L.
bougainvillea	*Bougainvillea spp.* Comm. ex Juss.
boxwood	*Buxus spp.* L.
broccoli	*Brassica oleracea* L. var. *botrytis* L.
brome grass	*Bromus spp.* L.
buckwheat	*Eriogonum spp.* Michx.
buffalo grass	*Buchloe dactyloides* (Nutt.) Engelm.
cabbage	*Brassica oleracea* L.
canola (rapeseed)	*Brassica napus* L.
cantaloupe	*Cucumis melo* L.
carrot	*Daucus carota* L. ssp. *sativus* (Hoffm.) Arcang.
cassava	*Manihot esculenta* Crantz
casuarina (sheoak)	*Casuarina spp.* Rumph. ex L.
cattail, common	*Typa latifolia* L.
cauliflower	*Brassica oleracea* L. (Botrytis group)
ceanothus	*Ceanothus spp*. L.
celery	*Apium graveolens* L. var. dulce (Mill.) Pers.
cherry, flowering	*Prunus serrulata* Lindl.
citrus	*Citrus spp.* L.
clover, alsike	*Trifolium hybridum* L.
clover, berseem	*Trifolium alexandrinum* L.
clover, crimson	*Trifolium incarnatum* L.
clover, ladino	*Trifolium repens* L.
clover, red	*Trifolium pratense* L.
clover, strawberry	*Trifolium fragiferum* L.
clover, sweet	*Melilotus indica* All
clover, white	*Trifolium repens* L.
coffee	*Coffea spp.* L.
corn	*Zea maiz* L.
cotton	*Gossypium hirsutum* L.
cottonwood	*Populus deltoidies* Bartr. Ex. Marsh
cowpea	*Vigna unguiculata* (L.) Walp.
cranberry	*Vaccinium macrocarpon* Ait.
cranberry, small	*Vaccinium oxycoccos L.*
cucumber	*Cucumis sativus* L.
currant	*Ribes spp.* L.
cypress, bald	*Taxodium distichum* (L.) L.C. Rich.
dallisgrass	*Paspalum dilatatum* Poir
dogwood	*Cornus spp.* L.
dogwood, grey	*Cornus racemosa* Lam.
elaeagnus	*Elaeagnus spp.* L.
elm	*Ulmus spp.* L.
elm, American	*Ulmus americana* L.
eucalyptus	*Eucalyptus spp.*
eucalyptus (jarrah)	*Eucalyptus marginata* Donn ex Sm.
fescue	*Festuca spp.* L.
fescue, meadow	*Festuca pratensis* Huds.
fescue, red	*Festuca rubra* L.
fescue, sheep	*Festuca ovina* L.
fescue, tall	*Festuca elatior* L.
fig	*Ficus carica* L.
filbert	*Corylus spp.* L.
fir, Douglas	*Pseudotsuga menziesii* (Mirbel) Franco
gamagrass, eastern	*Tripsacum dactyloides* (L.) L.
gliricidia (quickstick)	*Gliricidia sepium* (Jacq.) Kunth ex Walp.
grape	*Vitus spp.* L.
grapefruit	*Citrus paradisi* Macfad. (pro sp.) [*maxima sinensis*]

(continued)

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Plants Mentioned in This Text: Their Common and Scientific Names (Continued)

grevillea	*Grevillea spp.* R. Br. ex Knight
groundnut (peanut)	*Arachis hypogaea* L.
guayule	*Parthenium argentatum* Gray
gunnera	*Gunnera spp.* L.
harding grass	*Phalaris tuberosa* L. var. *stenoptera* (Hack) A.S. Hitchc.
hemlock, Canadian	*Tsuga canadensis* (L.) Carr.
hemlock, Carolina	*Tsuga caroliniana* Engelm.
hibiscus	*Hibiscus spp.* L.
hickory, bitternut	*Carya cordiformis* (Wangenh.) K. Koch
hickory, shagbark	*Carya ovata* (P. Mill.) K. Koch
holly, American	*Ilex opaca* Ait.
holly, burford	*Ilex cornuta* Lindl. & Paxton
honeysuckle	*Lonicera spp.* L.
hydrangea	*Hydrangea spp.* L.
ipil ipil tree	*Leucaena leucocephala* Benth.
jarrah	*Eucalyptus marginata* Donn ex Sm.
jojoba	*Simmondsia chinensis* (Link) Schneid.
juniper	*Juniperus spp.* L.
kale	*Brassica oleracea* L. (Acephala group)
kallargrass	*Leptochloa fusca* (L.) Kunth [syn. *Diplachne fusca* Beauv.]
kenaf	*Hibiscus cannabinus* L.
kochia, prostrate	*Kochia prostrata* (L.) Schrad.
kudzu	*Pueraria montana* (Lour.) Merr. Var. lobata (Wild.)
larch	*Larix spp.* P. Mill.
lemon	*Citrus limon* (L.) Burm. F.
lespedeza	*Lespedeza spp.* Michx.
lettuce	*Lactuca sativa* L.
leucaena (lead tree)	*Leucaena spp.* Benth.
lilac	*Syringa spp.* L.
linden	*Tillia spp.* L.
locust, black	*Robinia pseudoacacia* L.
locust, honey	*Gleditsia triacanthos* L.
lovegrass, weeping	*Eragrostis curvula* (Schrad.) Nees
lupine	*Lupinus spp.* L.
magnolia	*Magnolia spp.* L.
maiden cane	*Panicum hemitomon* J.A. Schultes
maize (corn)	*Zea mays* L.
mandarin orange	*Citrus reticulata* Blanco
manzanita	
maple	*Acer spp.* L.
maple, red	*Acer rubrum* L.
maple, sugar	*Acer saccharum* Marsh.
marigold	*Tagetes spp.*
milkvetch	*Astragalus spp.*
mosquito fern	*Azolla spp. L.*
mountain brome grass	*Bromus breviaristatus Buckl.*
mountain laurel	*Kalmia latifolia* L.
mulberry	*Morus spp.* L.
myrica	*Myrica spp.* L.
nut trees (e.g., almonds, hazelnuts)	*Prunus dulcis* (P. Mill.) D.A. Webber *Corylus spp.* L.
needlegrass	
oak	*Quercus spp.* L.
oak, blackjack	*Quercus marilandica* Muenchh.
oak, California scrub	
oak, chestnut	*Quercus prinus* L.
oak, northern red	*Quercus rubra* L.
oak, pin	*Quercus palustrus* Muenchh.
oak, southern red	*Quercus falcata* Michx.
oak, swamp white	*Quercus bicolor* Wild.
oak, white	*Quercus alba* L.
oak, willow	*Quercus pellos* L.
oats	*Avena sativa* L.
olive	*Olea europaea* L.
onion	*Allium cepa* L.
orange	*Citrus sinensis* (L.) Osbeck
orchard grass	*Dactylis glomerata* L.
pangola grass	*Digitaria eriantha* Steud.
pueraria, kudzu	*Pueraria phaseoloides* (Roxb.) Benth.
pea	*Pisum sativa* L.
pea, pigeon	*Cajanus cajan* (L.) Millsp.
peach	*Prunus persica* (L.) Batsch
peanut	*Arachis hypogaea* L.
pear	*Pyrus communis* L.
pecan	*Carya illinoinensis* (Wangenh.) K. Koch
phragmities reed	*Phragmities australis* (Cav.) Trin. Ex Steud.
pine, loblolly	*Pinus taeda* L.
pine, Monterey	*Pinus radiata* D. Don
pine, ponderosa	*Pinus ponderosa* Dougl. Ex P. & C. Laws.
pine, red	*Pinus resinosa* Ait.
pine, white	*Pinus strobus* L.
pine, white Scotch	*Pinus sylvestris* L.
pineapple	*Ananas comosus* (L.) Merrill
pitcher plant	*Sarracenia spp.* L.
plum (prune)	*Prunus domestica* L.
poinsettia	*Euphorbia pulcherrima* Willd. ex Klotzsch
pomegranate	*Punica granatum* L.
poplar	*Populus spp*. L.
potato	*Solanum tuberosum* L.
potato, sweet	*Ipomoea batatas* (L.) Lam.
povertygrass	*Danthonia spicata* (L.) Beauv. Ex Roem. & Schult.
privet	*Ligustrum spp.* L.
quickstick	*Gliricidia sepium* (Jacq.) Kunth ex Walp.
radish	*Raphanus sativus* L.

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Plants Mentioned in This Text: Their Common and Scientific Names (Continued)

rapeseed (see also canola)	*Brassica campestris* L. [syn. *B. rapa* L.]
raspberry	*Rubus idaeus* L.
red top	*Agrostis alba* L.
red top	*Agrostis gigantea* Roth
reed canarygrass	*Phalaris arundinacea* L.
rescuegrass	*Bromus catharticus* Vahl
rhododendron	*Rhododendron spp.* L.
rice	*Oryza spp.* L.
rice (paddy)	*Oryza sativa* L.
riverhemp, Egyptian	*Sesbania sesban* (L.) Merr.
rose-mallow, swamp	*Hibiscus moscheutos* L.
rosemary	*Rosmarinus officinalis* L.
roses	*Rosa spp.* L.
rye (grain, forage)	*Secale cereale* L.
rye, wild	*Elymus spp.*
ryegrass, perennial	*Lolium perenne* L.
safflower	*Carthamus tinctorius* L.
saltgrass, desert	*Distichlis spicta* L. var. *stricta* (Torr.) Bettle
sesbania	*Sesbania sesban* (L.) Merr.
skunk cabbage	*Symplocarpus foetidus* (L.) Salisb. Ex Nutt.
sorghum	*Sorghum bicolor* (L.) Moench
soy beans	*Glycine max* (L.) Merr.
spartina (cordgrass)	*Spartina spp.* Schreb.
spinach	*Spinacia oleracea* L.
spruce, black	*Picea mariana (Mill.) B.S.P.*
spruce, Norway	*Picea abies* (L.) Karst.
spruce, red	*Picea rubens* Sarg.
spruce, white	*Picea glauca* (Moench) Voss
squash	*Cucurbita pepo* L.
squash (zucchini)	*Cucurbita pepo* L. var. *melopepo* (L.) Alef.
star jasmine	*Jasminum multiflorum* (Burm. f.) Andr
strawberry	*Fragaria x ananassa* Duch.
sudan grass	*Sorghum sudanense* (Piper) Stapf
sugar beet	*Beta vulgaris* L.
sugar cane	*Saccharum officinarum* L.
sumac	*Rhus spp.* L.
sunflower	*Helianthus annuus* L.
sycamore	*Plantus occidentalis* L.
sweetgum	
tamarix (tamarisk)	*Tamarix gallica* L.
tea	*Camellia sinensis* (L.) O. Kuntze
teaberry	*Gaultheria procumbens* L.
timothy	*Phleum pratense* L.
tithonia	*Tithonia diversifolia* (Hemsl.) Gray
tobacco	*Nicotiana spp.* L.
tomato	*Solanum lycopersicum* L.
tree marigold	*Tithonia diversifolia* (Hemsl.) Gray
trefoil, birdsfoot	*Lotus corniculatus* L.
tulip poplar	*Liriodendron tulipifera* L.
turnip	*Brassica rapa* L. (Rapifera group)
velvetleaf	*Abutilon theophrasti* Medik.
vetch	*Vicia spp.* L.
vetch, common	*Vicia angustifolia* L.
vetch, hairy	*Vicia villosa* Roth
vetiver grass	*Vetiveria zizanioides* (L.) Nash ex Small
viburnum	*Viburnum spp.* L.
walnut	*Juglans spp.* L.
water melon	*Citrullus lanatus* (Thunb.) Matsumura & Nakai
water tupelo	*Nyssa aquatica* L.
wheat	*Triticum aestivum* L.
wheatgrass, crested	*Agropyron sibiricum* (Willd.) Beauvois
wheatgrass, fairway	*Agropyron cristatum* (L.) Gaertn.
wheatgrass, tall	*Agropyron elongatum* (Hort) Beauvois
wheatgrass, western	*Pascopyrum smithii* (Rydb.) A. Löve
wild rye, altai	*Leymus angustus* (Trin.) Pilger
wild rye, Russian	*Psathyrostachys juncea* (Fisch.) Nevski
willow	*Salix spp.* L.
willow, black	*Salix nigra* L.

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Glossary of Soil Science Terms[1]

A horizon The surface horizon of a mineral soil having maximum organic matter accumulation, maximum biological activity, and/or eluviation of materials such as iron and aluminum oxides and silicate clays.

abiotic Nonliving basic elements of the environment, such as rainfall, temperature, wind, and minerals.

accelerated erosion Erosion much more rapid than normal, natural, geological erosion; primarily as a result of the activities of humans or, in some cases, of animals.

acid cations Cations, principally Al^{3+}, Fe^{3+}, and H^+, that contribute to H^+ ion activity either directly or through hydrolysis reactions with water. *See also* nonacid cations.

acid rain Atmospheric precipitation with pH values less than about 5.6, the acidity being due to inorganic acids (such as nitric and sulfuric) that are formed when oxides of nitrogen and sulfur are emitted into the atmosphere.

acid saturation The proportion or percentage of a cation-exchange site occupied by acid cations.

acid soil A soil with a pH value <7.0. Usually applied to surface layer or root zone, but may be used to characterize any horizon. *See also* reaction, soil.

acid sulfate soils Soils that are potentially extremely acid (pH <3.5) because of the presence of large amounts of reduced forms of sulfur that are oxidized to sulfuric acid if the soils are exposed to oxygen when they are drained or excavated. A sulfuric horizon containing the yellow mineral jarosite is often present. *See also* cat clays.

acidity, active The activity of hydrogen ions in the aqueous phase of a soil. It is measured and expressed as a pH value.

acidity, residual Soil acidity that can be neutralized by lime or other alkaline materials but cannot be replaced by an unbuffered salt solution.

acidity, salt replaceable Exchangeable hydrogen and aluminum that can be replaced from an acid soil by an unbuffered salt solution such as KCl or NaCl.

acidity, total The total acidity in a soil. It is approximated by the sum of the salt-replaceable acidity plus the residual acidity.

Actinomycetes A group of bacteria that form branched mycelia that are thinner, but somewhat similar in appearance, to fungal hyphae. Includes many members of the order Actinomycetales.

activated sludge Sludge that has been aerated and subjected to bacterial action.

active layer The upper portion of a Gelisol that is subject to freezing and thawing and is underlain by permafrost.

active organic matter A portion of the soil organic matter that is relatively easily metabolized by microorganisms and cycles with a half-life in the soil of a few days to a few years.

adhesion Molecular attraction that holds the surfaces of two substances (e.g., water and sand particles) in contact.

adsorption The attraction of ions or compounds to the surface of a solid. Soil colloids adsorb large amounts of ions and water.

adsorption complex The group of organic and inorganic substances in soil capable of adsorbing ions and molecules.

aerate To impregnate with gas, usually air.

aeration, soil The process by which air in the soil is replaced by air from the atmosphere. In a well-aerated soil, the soil air is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain more carbon dioxide and correspondingly less oxygen than the atmosphere above the soil.

aerobic (1) Having molecular oxygen as a part of the environment. (2) Growing only in the presence of molecular oxygen, as aerobic organisms. (3) Occurring only in the presence of molecular oxygen (said of certain chemical or biochemical processes, such as aerobic decomposition).

aerosolic dust A type of eolian material that is very fine (about 1 to 10 μm) and may remain suspended in the air over distances of thousands of kilometers. Finer than most *loess*.

aggregate (soil) Many soil particles held in a single mass or cluster, such as a clod, crumb, block, or prism.

agric horizon A diagnostic subsurface horizon in which clay, silt, and humus derived from an overlying cultivated and fertilized layer have accumulated. Wormholes and illuvial clay, silt, and humus occupy at least 5% of the horizon by volume.

agroforestry Any type of multiple cropping land-use that entails complementary relations between trees and agricultural crops.

agronomy A specialization of agriculture concerned with the theory and practice of field-crop production and soil management. The scientific management of land.

air-dry (1) The state of dryness (of a soil) at equilibrium with the moisture content in the surrounding atmosphere. The actual moisture content will depend upon the relative humidity and the temperature of the surrounding atmosphere. (2) To allow to reach equilibrium in moisture content with the surrounding atmosphere.

air porosity The proportion of the bulk volume of soil that is filled with air at any given time or under a given condition, such as a specified moisture potential; usually the large pores.

albic horizon A diagnostic subsurface horizon from which clay and free iron oxides have been removed or in which the oxides have been segregated to the extent that the color of the horizon is determined primarily by the color of the primary sand and silt particles rather than by coatings on these particles.

Alfisols An order in *Soil Taxonomy*. Soils with gray to brown surface horizons, medium to high supply of bases, and B horizons of illuvial clay accumulation. These soils form mostly under forest or savanna vegetation in climates with slight to pronounced seasonal moisture deficit.

algal bloom A population explosion of algae in surface waters, such as lakes and streams, often resulting in high turbidity and green- or red-colored water, and commonly stimulated by nutrient enrichment with phosphorus and nitrogen.

alkaline soil Any soil that has pH > 7. Usually applied to the surface layer or root zone but may be used to characterize any horizon or a sample thereof. *See also* reaction, soil.

allelochemical An organic chemical by which one plant can influence another. *See* allelopathy.

allelopathy The process by which one plant may affect other plants by biologically active chemicals introduced into the soil, either directly by leaching or exudation from the source plant, or as a result of the decay of the plant residues. The effects, though usually negative, may also be positive.

allophane A poorly defined aluminosilicate mineral whose structural framework consists of short runs of three-dimensional crystals interspersed with amorphous noncrystalline materials. Along with its more weathered

[1]This glossary was compiled and modified from several sources, including *Online Glossary of Soil Science Terms* [Madison, Wis.: Soil Sci. Soc. Amer. (2015)] *Resource Conservation Glossary* [Anheny, Iowa: Soil Cons. Soc. Amer. (1982)], and *Soil Taxonomy* [Washington, D.C.: U.S. Department of Agriculture (1999)].

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companion, it is prevalent in volcanic ash materials.

alluvial fan Fan-shaped alluvium deposited at the mouth of a canyon or ravine where debris-laden waters fan out, slow down, and deposit their burden.

alluvium A general term for all detrital material deposited or in transit by streams, including gravel, sand, silt, clay, and all variations and mixtures of these. Unless otherwise noted, alluvium is unconsolidated.

alpha particle A positively charged particle (consisting of two protons and two neutrons) that is emitted by certain radioactive compounds.

aluminosilicates Compounds containing aluminum, silicon, and oxygen as main constituents. An example is microcline, $KAlSi_3O_8$.

amendment, soil Any substance other than fertilizers, such as lime, sulfur, gypsum, and sawdust, used to alter the chemical or physical properties of a soil, generally to make it more productive.

amino acids Nitrogen-containing organic acids that couple together to form proteins. Each acid molecule contains one or more amino groups (—NH_2) and at least one carboxyl group (—COOH). In addition, some amino acids contain sulfur.

Ammanox A biochemical process in the N cycle by which certain anaerobic bacteria or archaea oxidize ammonium ions using nitrite ions as the electron acceptor, the main product being N_2 gas.

ammonification The biochemical process whereby ammoniacal nitrogen is released from nitrogen-containing organic compounds.

ammonium fixation The entrapment of ammonium ions by the mineral or organic fractions of the soil in forms that are insoluble in water and are at least temporarily nonexchangeable.

amorphous material Noncrystalline constituents of soils.

anaerobic (i) The absence of molecular oxygen. (ii) Growing or occurring in the absence of molecular oxygen (e.g., anaerobic bacteria or biochemical reduction reaction).

anaerobic respiration The metabolic process whereby electrons are transferred from a reduced compound (usually organic) to an inorganic acceptor molecule other than oxygen.

andic properties Soil properties related to volcanic origin of materials, including high organic carbon content, low bulk density, high phosphate retention, and extractable iron and aluminum.

Andisols An order in *Soil Taxonomy*. Soils developed from volcanic ejecta. The colloidal fraction is dominated by allophane and/or Al-humus compounds.

angle of repose The maximum slope steepness at which loose, cohesionless material will come to rest.

anion Negatively charged ion; during electrolysis it is attracted to the positively charged anode.

anion exchange Exchange of anions in the soil solution for anions adsorbed on the surface of clay and humus particles.

anion exchange capacity The sum total of exchangeable anions that a soil can adsorb. Expressed as centimoles of charge per kilogram (cmol*c*/kg) of soil (or of other adsorbing material, such as clay).

anoxic *See* anaerobic.

anthropic epipedon A thick horizon that formed in material that was inentionally alltered or transported by humans. It usually contains humans artifacts and/or is located in a human altered landscape feature (mounds, pit, terraces, etc.).

antibiotic A substance produced by one species of organism that, in low concentrations, will kill or inhibit growth of certain other organisms.

Ap The surface layer of a soil disturbed by cultivation or pasturing.

apatite A naturally occurring complex calcium phosphate that is the original source of most of the phosphate fertilizers. Formulas such as $[3Ca_3(PO_4)_2] \cdot CaF_2$ illustrate the complex compounds that make up apatite.

aquic conditions Continuous or periodic saturation (with water) and reduction, commonly indicated by redoximorphic features.

aquiclude A saturated body of rock or sediment that is incapable of transmitting significant quantities of water under ordinary water pressures.

aquifer A saturated, permeable layer of sediment or rock that can transmit significant quantities of water under normal pressure conditions.

arbuscular mycorrhiza A common endomycorrhizal association produced by phycomycetous fungi and characterized by the development, within root cells, of small structures known as *arbuscules*. Some also form, between root cells, storage organs known as *vesicles*. Host range includes many agricultural and horticultural crops. Formerly called vesicular arbuscular mycorrhiza (VAM). *See also* endotrophic mycorrhiza.

arbuscule Specialized branched structure formed within a root cortical cell by endotrophic mycorrhizal fungi.

Archaea One of the two domains of single-celled prokaryote microorganisms. Includes organisms adapted to extremes of salinity and heat, and those that subsist on methane. Similar appearing, but evolutionarily distinct from bacteria.

argillan A thin coating of well-oriented clay particles on the surface of a soil aggregate, particle, or pore. A clay film.

argillic horizon A diagnostic subsurface horizon characterized by the illuvial accumulation of layer-lattice silicate clays.

arid climate Climate in regions that lack sufficient moisture for crop production without irrigation. In cool regions annual precipitation is usually less than 25 cm. It may be as high as 50 cm in tropical regions. Natural vegetation is desert shrubs.

Aridisols An order in *Soil Taxonomy*. Soils of dry climates. They have pedogenic horizons, low in organic matter, that are never moist for as long as three consecutive months. They have an ochric epipedon and one or more of the following diagnostic horizons: argillic, natric, cambic, calcic, petrocalcic, gypsic, petrogypsic, salic, or a duripan.

aspect (of slopes) The direction (e.g., south or north) that a slope faces with respect to the sun.

association, soil *See* soil association.

Atterberg limits Water contents of fine-grained soils at different states of consistency.

liquid limit (LL) The water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil.

plastic limit (PL) The water content corresponding to an arbitrary limit between the plastic and semisolid states of consistency of a soil.

autochthonous organisms Those microorganisms thought to subsist on the more resistant soil organic matter and little affected by the addition of fresh organic materials. *Contrast with* zymogenous organisms. *See also* k-strategist.

autotroph An organism capable of utilizing carbon dioxide or carbonates as the sole source of carbon and obtaining energy for life processes from the oxidation of inorganic elements or compounds such as iron, sulfur, hydrogen, ammonium, and nitrites, or from radiant energy. *Contrast with* heterotroph.

available nutrient That portion of any element or compound in the soil that can be readily absorbed and assimilated by growing plants. ("Available" should not be confused with "exchangeable.")

available water The portion of water in a soil that can be readily absorbed by plant roots. The amount of water released between the field capacity and the permanent wilting point.

B horizon A soil horizon, usually beneath the A or E horizon, that is characterized by one or more of the following: (1) a concentration of soluble salts, silicate clays, iron and aluminum oxides, and humus, alone or in

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combination; (2) a blocky or prismatic structure; and (3) coatings of iron and aluminum oxides that give darker, stronger, or redder color.

Bacteria One of two domains of single-celled prokaryote microorganisms. Includes all that are not Archaea.

bar A unit of pressure equal to 1 million dynes per square centimeter (10^6 dynes/cm^2). It approximates the pressure of a standard atmosphere.

base flow The flux or flow of water in a stream fed by groundwater during periods without precipitation. Opposite of *storm flow*.

base-forming cations (Obsolete) Those cations that form strong (strongly dissociated) bases by reaction with hydroxyl; e.g., K^+ forms potassium hydroxide (K^+ + OH). *See* nonacid cations.

base saturation percentage The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen and aluminum. It is expressed as a percentage of the total cation exchange capacity. *See* nonacid saturation.

bedding (Engineering) Arranging the surface of fields by plowing and grading into a series of elevated beds separated by shallow depressions or ditches for drainage.

bedrock The solid rock underlying soils and the regolith in depths ranging from zero (where exposed by erosion) to several hundred feet.

bench terrace An embankment constructed across sloping fields with a steep drop on the downslope side.

beta particle A high-speed electron emitted in radioactive decay.

bioaccumulation A buildup within an organism of specific compounds due to biological processes. Commonly applied to heavy metals, pesticides, or metabolites.

bioaugmentation The cleanup of contaminated soils by adding exotic microorganisms that are especially efficient at breaking down an organic contaminant. A form of *bioremediation*.

biochar A black carbon condensate product purposefully made by heating organic material at 300 to 700 °C under low oxygen conditions.

biodegradable Subject to degradation by biochemical processes.

biological nitrogen fixation Occurs at ordinary temperatures and pressures. It is commonly carried out by certain bacteria, algae, and actinomycetes, which may or may not be associated with higher plants.

biomass The total mass of living material of a specified type (e.g., microbial biomass) in a given environment (e.g., in a cubic meter of soil).

biopores Soil pores, usually of relatively large diameter, created by plant roots, earthworms, or other soil organisms.

bioremediation The decontamination or restoration of polluted or degraded soils by means of enhancing the chemical degradation or other activities of soil organisms.

biosequence A group of related soils that differ, one from the other, primarily because of differences in kinds and numbers of plants and soil organisms as a soil-forming factor.

biosolids Sewage sludge that meets certain regulatory standards, making it suitable for land application. *See* sewage sludge.

biostimulation The cleanup of contaminated soils through the manipulation of nutrients or other soil environmental factors to enhance the activity of naturally occurring soil microorganisms. A form of *bioremediation*.

blocky soil structure Soil aggregates with blocklike shapes; common in B horizons of soils in humid regions.

broad-base terrace A low embankment with such gentle slopes that it can be farmed, constructed across sloping fields to reduce erosion and runoff.

broadcast Scatter seed or fertilizer on the surface of the soil.

brownfields Abandoned, idled, or underused industrial and commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination.

buffering capacity The ability of a soil to resist changes in pH. Commonly determined by presence of clay, humus, and other colloidal materials.

bulk blended fertilizers Solid fertilizer materials blended together in small blending plants, delivered to the farm in bulk, and usually spread directly on the fields by truck or other special applicator.

bulk blending Mixing dry individual granulated fertilizer materials to form a mixed fertilizer that is applied promptly to the soil.

bulk density, soil The mass of dry soil per unit of bulk volume, including the air space. The bulk volume is determined before drying to constant weight at 105 °C.

buried soil Soil covered by an alluvial, loessal, or other deposit, usually to a depth greater than the thickness of the solum.

by-pass flow *See* preferential flow.

C horizon A mineral horizon, generally beneath the solum, that is relatively unaffected by biological activity and pedogenesis and is lacking properties diagnostic of an A or B horizon. It may or may not be like the material from which the A and B have formed.

calcareous soil Soil containing sufficient calcium carbonate (often with magnesium carbonate) to effervesce visibly when treated with cold 0.1 N hydrochloric acid.

calcic horizon A diagnostic subsurface horizon of secondary carbonate enrichment that is more than 15 cm thick, has a calcium carbonate equivalent of more than 15%, and has at least 5% more calcium carbonate equivalent than the underlying C horizon.

caliche A layer near the surface, more or less cemented by secondary carbonates of calcium or magnesium precipitated from the soil solution. It may occur as a soft, thin soil horizon; as a hard, thick bed just beneath the solum; or as a surface layer exposed by erosion.

cambic horizon A diagnostic subsurface horizon that has a texture of loamy very fine sand or finer, contains some weatherable minerals, and is characterized by the alteration or removal of mineral material. The cambic horizon lacks cementation or induration and has too few evidences of illuviation to meet the requirements of the argillic or spodic horizon.

capillary conductivity (Obsolete) *See* hydraulic conductivity.

capillary fringe A zone in the soil just above the plane of zero water pressure (water table) that remains saturated or almost saturated with water.

capillary water The water held in the capillary or *small* pores of a soil, usually with a tension >60 cm of water. *See also* soil water potential.

carbon cycle The sequence of transformations whereby carbon dioxide is fixed in living organisms by photosynthesis or by chemosynthesis, liberated by respiration and by the death and decomposition of the fixing organism, used by heterotrophic species, and ultimately returned to its original state.

carbon/nitrogen ratio The ratio of the weight of organic carbon (C) to the weight of total nitrogen (N) in a soil or in organic material.

carnivore An organism that feeds on animals.

casts, earthworm Rounded, water-stable aggregates of soil that have passed through the gut of an earthworm.

cat clays Wet clay soils high in reduced forms of sulfur that, upon being drained, become extremely acid because of the oxidation of the sulfur compounds and the formation of sulfuric acid. Usually found in tidal marshes. *See* acid sulfate soils.

catena A group of soils that commonly occur together in a landscape, each characterized by a different slope position and resulting set of drainage-related proprieties. *See also* toposequence.

cation A positively charged ion; during electrolysis it is attracted to the negatively charged cathode.

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cation exchange The interchange between a cation in solution and another cation on the surface of any surface-active material, such as clay or organic matter.

cation exchange capacity The sum total of exchangeable cations that a soil can adsorb. Sometimes called *total-exchange capacity, base-exchange capacity*, or *cation-adsorption capacity*. Expressed in centimoles of charge per kilogram (cmol*c*/kg) of soil (or of other adsorbing material, such as clay).

cemented Indurated; having a hard, brittle consistency because the particles are held together by cementing substances, such as humus, calcium carbonate, or the oxides of silicon, iron, and aluminum.

channery Thin, flat fragments of limestone, sandstone, or schist up to 15 cm (6 in.) in major diameter.

char An important component of stable soil organic carbon created by natural fires that heat organic material under low oxygen conditions to cause charring rather than burning. Char generally has very high aromaticity, surface area, and water holding capacity.

chelate (Greek, claw) A type of chemical compound in which a metallic ion is firmly combined with an organic molecule by means of multiple chemical bonds.

chert A structureless form of silica, closely related to flint, that breaks into angular fragments.

chisel, subsoil A tillage implement with one or more cultivator-type feet to which are attached strong knifelike units used to shatter or loosen hard, compact layers, usually in the subsoil, to depths below normal plow depth. *See also* subsoiling.

chlorite A 2:1:1-type layer-structured silicate mineral having 2:1 layers alternating with a magnesium-dominated octahedral sheet.

chlorosis A condition in plants relating to the failure of chlorophyll (the green coloring matter) to develop. Chlorotic leaves range from light green through yellow to almost white.

chroma (color) *See* Munsell color system.

chronosequence A sequence of related soils that differ, one from the other, in certain properties primarily as a result of time as a soil-forming factor.

classification, soil *See* soil classification.

clay (1) A soil separate consisting of particles <0.002 mm in equivalent diameter. (2) A soil textural class containing >40% clay, <45% sand, and <40% silt.

clay mineral Naturally occurring inorganic material (usually crystalline) found in soils and other earthy deposits, the particles being of clay size, that is, <0.002 mm in diameter.

claypan A dense, compact, slowly permeable layer in the subsoil having a much higher clay content than the overlying material, from which it is separated by a sharply defined boundary. Claypans are usually hard when dry and plastic and sticky when wet. *See also* hardpan.

climosequence A group of related soils that differ, one from another, primarily because of differences in climate as a soil-forming factor.

clod A compact, coherent mass of soil produced artificially, usually by such human activities as plowing and digging, especially when these operations are performed on soils that are either too wet or too dry for normal tillage operations.

coarse fragments Mineral (rock) soil particles larger than 2 mm in diameter. *Compare to* fine earth fraction.

coarse texture The texture exhibited by sands, loamy sands, and sandy loams (except very fine sandy loam).

cobblestone Rounded or partially rounded rock or mineral fragments 7.5 to 25 cm (3 to 10 in.) in diameter.

co-composting A method of composting in which two materials of differing but complementary nature are mingled together and enhance each other's decomposition in a compost system.

cohesion Holding together: force holding a solid or liquid together, owing to attraction between like molecules. Decreases with rise in temperature.

collapsible soil Certain soil that may undergo a sudden loss in strength when wetted.

colloid, soil (Greek, gluelike) Organic and inorganic matter with very small particle size and a correspondingly large surface area per unit of mass.

colluvium A deposit of rock fragments and soil material accumulated at the base of steep slopes as a result of gravitational action.

color The property of an object that depends on the wavelength of light it reflects or emits.

columnar soil structure *See* soil structure types.

companion planting The practice of growing certain species of plants in close proximity because one species has the effect of improving the growth of the other, sometimes by positive *allelopathic* effects.

compost Organic residues, or a mixture of organic residues and soil, that have been piled, moistened, and allowed to undergo biological decomposition. Mineral fertilizers are sometimes added. Often called *artificial manure* or *synthetic manure* if produced primarily from plant residues.

concretion A local concentration of a chemical compound, such as calcium carbonate or iron oxide, in the form of grains or nodules of varying size, shape, hardness, and color.

conduction The transfer of heat by physical contact between two or more objects.

conductivity, hydraulic *See* hydraulic conductivity.

conservation tillage *See* tillage, conservation.

consistence The combination of properties of soil material that determine its resistance to crushing and its ability to be molded or changed in shape. Such terms as *loose, friable, firm, soft, plastic*, and *sticky* describe soil consistence.

consistency The interaction of adhesive and cohesive forces within a soil at various moisture contents as expressed by the relative ease with which the soil can be deformed or ruptured.

consociation *See* soil consociation.

consolidation test A laboratory test in which a soil mass is laterally confined within a ring and is compressed with a known force between two porous plates.

constant charge The net surface charge of mineral particles, the magnitude of which depends only on the chemical and structural composition of the mineral. The charge arises from isomorphous substitution and is not affected by soil pH.

consumptive use The water used by plants in transpiration and growth, plus water vapor loss from adjacent soil or snow, or from intercepted precipitation in any specified time. Usually expressed as equivalent depth of free water per unit of time.

contour An imaginary line connecting points of equal elevation on the surface of the soil. A contour terrace is laid out on a sloping soil at right angles to the direction of the slope and nearly level throughout its course.

contour strip-cropping Layout of crops in comparatively narrow strips in which the farming operations are performed approximately on the contour. Usually strips of grass, close-growing crops, or fallow are alternated with those of cultivated crops.

controlled traffic A farming system in which all wheeled traffic is confined to fixed paths so that repeated compaction of the soil does not occur outside the selected paths.

convection The transfer of heat through a gas or solution because of molecular movement.

cover crop A close-growing crop grown primarily for the purpose of protecting and improving soil between periods of regular crop production or between trees and vines in orchards and vineyards.

creep Slow mass movement of soil and soil material down relatively steep slopes, primarily under the influence of gravity, but facilitated by saturation with water and by alternate freezing and thawing.

crop rotation A planned sequence of crops growing in a regularly recurring succession on the same area of land, as contrasted to continuous culture of one crop or growing different crops in haphazard order.

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crotovina A former animal burrow in one soil horizon that has been filled with organic matter or material from another horizon (also spelled *krotovina*).

crumb A soft, porous, more or less rounded natural unit of structure from 1 to 5 mm in diameter. *See also* soil structure types.

crushing strength The force required to crush a mass of dry soil or, conversely, the resistance of the dry soil mass to crushing. Expressed in units of force per unit area (pressure).

crust (soil) (i) physical A surface layer on soils, ranging in thickness from a few millimeters to as much as 3 cm, that physical-chemical processes have caused to be much more compact, hard, and brittle when dry than the material immediately beneath it.

(ii) microbiotic An assemblage of cyanobacteria, algae, lichens, liverworts, and mosses that commonly forms an irregular crust on the soil surface, especially on otherwise barren, arid-region soils. Also referred to as cryptogamic, cryptobiotic, or biological crusts.

cryophilic Pertaining to low temperatures in the range of 5 to 15 °C, the range in which cryophilic organisms grow best.

cryoturbation Physical disruption and displacement of soil material within the profile by the forces of freezing and thawing. Sometimes called *frost churning*, it results in irregular, broken horizons, involutions, oriented rock fragments, and accumulation of organic matter on the permafrost table.

cryptogam *See* crust (ii) microbiotic.

crystal A homogeneous inorganic substance of definite chemical composition bounded by planar surfaces that form definite angles with each other, thus giving the substance a regular geometrical form.

crystal structure The orderly arrangement of atoms in a crystalline material.

cultivation A tillage operation used in preparing land for seeding or transplanting or later for weed control and for loosening the soil.

cutans A modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents; e.g. "clay skins."

cyanobacteria Chlorophyll-containing bacteria that accommodate both photosynthesis and nitrogen fixation. Formerly called blue-green algae.

deciduous plant A plant that sheds all its leaves every year at a certain season.

decomposition Chemical breakdown of a compound (e.g., a mineral or organic compound) into simpler compounds, often accomplished with the aid of microorganisms.

deflocculate (1) To separate the individual components of compound particles by chemical and/or physical means. (2) To cause the particles of the *disperse phase* of a colloidal system to become suspended in the *dispersion medium*.

delineation An individual polygon shown by a closed boundary on a soil map that defines the area, shape, and location of a map unit within a landscape.

delivery ratio The ratio of eroded sediment carried out of a drainage basin to the total amount of sediment moved within the basin by erosion processes.

delta An alluvial deposit formed where a stream or river drops its sediment load upon entering a quieter body of water.

denitrification The biochemical reduction of nitrate or nitrite to gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen.

density *See* particle density; bulk density.

depletion zone The volume of soil solution adjacent to plant roots where the concentration of an element has been reduced by plant uptake that is faster than diffusion can replace the element from the bulk solution. Often used in reference to phosphorus or potassium.

desalinization Removal of salts from saline soil, usually by leaching.

desert crust A hard layer, containing calcium carbonate, gypsum, or other binding material, exposed at the surface in desert regions.

desert pavement A natural residual concentration of closely packed pebbles, boulders, and other rock fragments on a desert surface where wind and water action has removed all smaller particles.

desert varnish A thin, dark, shiny film or coating of iron oxide and lesser amounts of manganese oxide and silica formed on the surfaces of pebbles, boulders, rock fragments, and rock outcrops in arid regions.

desorption The removal of sorbed material from surfaces.

detritivore An organism that subsists on detritus.

detritus Debris from dead plants and animals.

diagnostic horizons (As used in *Soil Taxonomy*): Horizons having specific soil characteristics that are indicative of certain classes of soils. Horizons that occur at the soil surface are called *epipedons;* those below the surface, *diagnostic subsurface horizons*.

diatomaceous earth A geologic deposit of fine, grayish, siliceous material composed chiefly or wholly of the remains of diatoms. It may occur as a powder or as a porous, rigid material.

diatoms Algae having siliceous cell walls that persist as a skeleton after death; any of the microscopic unicellular or colonial algae constituting the class Bacillariaceae. They occur abundantly in fresh and salt waters and their remains are widely distributed in soils.

diffusion The movement of atoms in a gaseous mixture or of ions in a solution, primarily as a result of their own random motion.

dioctahedral sheet An octahedral sheet of silicate clays in which the sites for the six-coordinated metallic atoms are mostly filled with trivalent atoms, such as $A1^{3+}$.

disintegration Physical or mechanical breakup or separation of a substance into its component parts (e.g., a rock breaking into its mineral components).

disperse (1) To break up compound particles, such as aggregates, into the individual component particles. (2) To distribute or suspend fine particles, such as clay, in or throughout a dispersion medium, such as water.

Dissimilatory nitrate reduction to ammonium (DNRA) A bacterial process by which nitrate is converted to ammonium under a wide range of oxygen and carbon levels. Compare to dentrification (a different type of dissimilatory nitrate reduction) which is strictly anaerobic and requires an energy source.

dissolution Process by which molecules of a gas, solid, or another liquid dissolve in a liquid, thereby becoming completely and uniformly dispersed throughout the liquid's volume.

distribution coefficient (K_d) The distribution of a chemical between soil and water.

diversion terrace *See* terrace.

drain (1) To provide channels, such as open ditches or drain tile, so that excess water can be removed by surface or by internal flow. (2) To lose water (from the soil) by percolation.

drain field, septic tank An area of soil into which the effluent from a septic tank is piped so that it will drain through the lower part of the soil profile for disposal and purification.

drainage, soil The frequency and duration of periods when the soil is free from saturation with water.

drift Material of any sort deposited by geological processes in one place after having been removed from another. Glacial drift includes material moved by the glaciers and by the streams and lakes associated with them.

drumlin Long, smooth, cigar-shaped low hills of glacial till, with their long axes parallel to the direction of ice movement.

dryland farming The practice of crop production in low-rainfall areas without irrigation.

duff The matted, partly decomposed organic surface layer of forest soils.

duripan A diagnostic subsurface horizon that is cemented by silica, to the point that air-dry fragments will not slake in water or HCL. Hardpan.

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dust mulch A loose, finely granular or powdery condition on the surface of the soil, usually produced by shallow cultivation.

E horizon Horizon characterized by maximum illuviation (washing out) of silicate clays and iron and aluminum oxides; commonly occurs above the B horizon and below the A horizon.

earthworms Animals of the Lumbricidae family that burrow into and live in the soil. They mix plant residues into the soil and improve soil aeration.

ecosystem A dynamic and interacting combination of all the living organisms and nonliving elements (matter and energy) of an area.

ecosystem services Products of natural ecosystems that support and fulfill the needs of human beings. Provision of clean water and unpolluted air are examples.

ectotrophic mycorrhiza (ectomycorrhiza) A symbiotic association of the mycelium of fungi and the roots of certain plants in which the fungal hyphae form a compact mantle on the surface of the roots and extend into the surrounding soil and inward between cortical cells, but not into these cells. Associated primarily with certain trees. *See also* endotrophic mycorrhiza.

edaphology The science that deals with the influence of soils on living things, particularly plants, including human use of land for plant growth.

effective cation exchange capacity The amount of cation charges that a material (usually soil or soil colloids) can hold at the pH of the material, measured as the sum of the exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, and expressed as moles or cmol of charge per kg of material. *See* cation exchange capacity.

effective precipitation That portion of the total precipitation that becomes available for plant growth or for the promotion of soil formation.

E_h In soils, it is the potential created by oxidation-reduction reactions that take place on the surface of a platinum electrode measured against a reference electrode, minus the Eh of the reference electrode. This is a measure of the oxidation-reduction potential of electrode-reactive components in the soil. *See also* pe.

electrical conductivity (EC) The capacity of a substance to conduct or transmit electrical current. In soils or water, measured in siemens/meter (or often dS/m), and related to dissolved solutes.

eluviation The removal of soil material in suspension (or in solution) from a layer or layers of a soil. Usually, the loss of material in solution is described by the term "leaching." *See also* illuviation and leaching.

endoaquic (endosaturation) A condition or moisture regime in which the soil is saturated with water in all layers from the upper boundary of saturation (water table) to a depth of 200 cm or more from the mineral soil surface. *See also* epiaquic.

endotrophic mycorrhiza (endomycorrhiza) A symbiotic association of the mycelium of fungi and roots of a variety of plants in which the fungal hyphae penetrate directly into root hairs, other epidermal cells, and occasionally into cortical cells. Individual hyphae also extend from the root surface outward into the surrounding soil. *See also* arbuscular mycorrhiza.

enrichment ratio The concentration of a substance (e.g., phosphorus) in eroded sediment divided by its concentration in the source soil prior to being eroded.

Entisols An order in *Soil Taxonomy*. Soils that have no diagnostic pedogenic horizons. They may be found in virtually any climate on very recent geomorphic surfaces.

eolian soil material Soil material accumulated through wind action. The most extensive areas in the United States are silty deposits (loess), but large areas of sandy deposits also occur.

epiaquic (episaturation) A condition in which the soil is saturated with water due to a perched water table in one or more layers within 200 cm of the mineral soil surface, implying that there are also one or more unsaturated layers within 200 cm below the saturated layer. *See also* endoaquic.

epipedon A diagnostic surface horizon that includes the upper part of the soil that is darkened by organic matter, or the upper eluvial horizons, or both. *(Soil Taxonomy.)*

equilibrium phosphorus concentration The concentration of phosphorus in a solution in equilibrium with a soil, the EPC_0 being the concentration of phosphorus achieved by desorption of phosphorus from a soil to phosphorus-free distilled water.

erosion (1) The wearing away of the land surface by running water, wind, ice, or other geological agents, including such processes as gravitational creep. (2) Detachment and movement of soil or rock by water, wind, ice, or gravity.

esker A narrow ridge of gravelly or sandy glacial material deposited by a stream in an ice-walled valley or tunnel in a receding glacier.

essential element A chemical element required for the normal growth of plants.

eukaryote An organism whose cells each have a visibly evident nucleus.

eutrophic Having concentrations of nutrients optimal (or nearly so) for plant or animal growth. (Said of algal-enriched bodies of water)

eutrophication Nutrient enrichment of lakes, ponds, and other such waters that stimulates the growth of aquatic organisms, which leads to a deficiency of oxygen in the water body.

evapotranspiration The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants.

exchange capacity The total ionic charge of the adsorption complex active in the adsorption of ions. *See also* anion exchange capacity; cation exchange capacity.

exchangeable ions Positively or negatively charged atoms or groups of atoms that are held on or near the surface of a solid particle by attraction to charges of the opposite sign, and which may be replaced by other like-charged ions in the soil solution.

exchangeable sodium percentage The extent to which the adsorption complex of a soil is occupied by sodium. It is expressed as follows:

$$\text{ESP} = \frac{\text{exchngeable sodium (cmol}_c\text{/kg soil)}}{\text{cation exchange capacity (cmol}_c\text{/kg soil)}} \times 100$$

exfoliation Peeling away of layers of a rock from the surface inward, usually as the result of expansion and contraction that accompany changes in temperature.

expansive soil Soil that undergoes significant volume change upon wetting and drying, usually because of a high content of swelling-type clay minerals.

external surface The area of surface exposed on the top, bottom, and sides of a clay crystal.

facultative organism An organism capable of both aerobic and anaerobic metabolism.

fallow Cropland left idle in order to restore productivity, mainly through accumulation of nutrients, water, and/or organic matter. Preceding a cereal grain crop in semiarid regions, land may be left in *summer fallow* for a period during which weeds are controlled by chemicals or tillage and water is allowed to accumulate in the soil profile. In humid regions, fallow land may be allowed to grow up in natural vegetation for a period ranging from a few months to many years. *Improved fallow* involves the purposeful establishment of plant species capable of restoring soil productivity more rapidly than a natural plant succession.

family, soil In *Soil Taxonomy*, one of the categories intermediate between the great group and the soil series. Families are defined largely on the basis of physical and mineralogical properties of importance to plant growth.

fauna The animal life of a region or ecosystem.

fen A calcium-rich, peat-accumulating wetland with relatively stagnant water.

ferrihydrite, $Fe_5HO_8 \cdot 4H_2O$ A dark reddish brown poorly crystalline iron oxide that forms in wet soils.

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fertigation The application of fertilizers in irrigation waters, commonly through sprinkler systems.

fertility, soil The quality of a soil that enables it to provide essential chemical elements in quantities and proportions for the growth of specified plants.

fertilizer Any organic or inorganic material of natural or synthetic origin added to a soil to supply certain elements essential to the growth of plants.

fibric materials *See* organic soil materials.

field capacity (field moisture capacity) The percentage of water remaining in a soil two or three days after its having been saturated and after free drainage has practically ceased.

fine earth fraction That portion of the soil that passes through a 2 mm diameter sieve opening. *Compare to* coarse fragments.

fine texture Consisting of or containing large quantities of the fine fractions, particularly of silt and clay. (Includes clay loam, sandy clay loam, silty clay loam, sandy clay, silty clay, and clay textural classes.)

fine-grained mica A silicate clay having a 2:1-type lattice structure with much of the silicon in the tetrahedral sheet having been replaced by aluminum and with considerable interlayer potassium, which binds the layers together, prevents interlayer expansion and swelling, and limits interlayer cation exchange capacity.

fixation (1) For other than elemental nitrogen: the process or processes in a soil by which certain chemical elements are converted from a soluble or exchangeable form to a much less soluble or to a nonexchangeable form; for example, potassium, ammonium, and phosphorus fixation. (2) For elemental nitrogen: process by which gaseous elemental nitrogen is chemically combined with hydrogen to form ammonia. *See* biological nitrogen fixation.

flagstone A relatively thin rock or mineral fragment 15 to 38 cm in length commonly composed of shale, slate, limestone, or sandstone.

flocculate To aggregate or clump together individual, tiny soil particles, especially fine clay, into small clumps or floccules. Opposite of *deflocculate* or *disperse*.

floodplain The land bordering a stream, built up of sediments from overflow of the stream and subject to inundation when the stream is at flood stage. Sometimes called *bottomland*.

flora The sum total of the kinds of plants in an area at one time. The organisms loosely considered to be of the plant kingdom.

fluorapatite A member of the apatite group of minerals containing fluorine. Most common mineral in phosphate rock.

fluvial deposits Deposits of parent materials laid down by rivers or streams.

fluvioglacial *See* glaciofluvial deposits.

foliar diagnosis An estimation of mineral nutrient deficiencies (excesses) of plants based on examination of the chemical composition of selected plant parts, and the color and growth characteristics of the foliage of the plants.

food web The community of organisms that relate to one another by sharing and passing on food substances. They are organized into trophic levels such as producers that create organic substances from sunlight and inorganic matter, to consumers and predators that eat the producers, dead organisms, waste products and each other.

forest floor The forest soil O horizons, including litter and unincorporated humus, on the mineral soil surface.

fraction A portion of a larger store of a substance operationally defined by a particular analysis or separation method. For example, the particulate organic matter fraction of soil organic matter is defined by a series of laboratory procedures by which it is separated. *Compare* to pool.

fragipan Dense and brittle pan or subsurface layer in soils that owes its hardness mainly to extreme density or compactness rather than high clay content or cementation. Removed fragments are friable, but the material in place is so dense that roots penetrate and water moves through it very slowly.

friable A soil consistency term pertaining to soils that crumble with ease.

frigid A soil temperature class with mean annual temperature below 8 °C.

fritted micronutrients Sintered silicates having total guaranteed analyses of micronutrients with controlled (relatively slow) release characteristics.

fulvic acid A term of varied usage but usually referring to a mixture of organic substances soluble in both alkali and acid solution. Found in natural waters, sediments and to a limited extent in aerobic soils. Once thought to be a major constituent of soil organic matter.

functional diversity The characteristic of an ecosystem exemplified by the capacity to carry out a large number of biochemical transformations and other functions.

functional group An atom, or group of atoms, attached to a large molecule. Each functional group (e.g., —OH, —CH_3, —COOH, etc.) has a characteristic chemical reactivity.

fungi Eukaryote microorganisms with a rigid cell wall. Some form long filaments of cells called *hyphae* that may grow together to form a visible body.

furrow slice The uppermost layer of an arable soil to the depth of primary tillage; the layer of soil sliced away from the rest of the profile and inverted by a moldboard plow.

gabion Partitioned, wire fabric containers, filled with stone at the site of use, to form flexible, permeable, and monolithic structures for earth retention.

gamma ray A high-energy ray (photon) emitted during radioactive decay of certain elements.

Gelisols An order in *Soil Taxonomy*. Soils that have permafrost within the upper 1 m, or upper 2 m if cryoturbation is also present. They may have an ochric, histic, mollic, or other epipedon.

gellic materials Mineral or organic soil materials that have *cryoturbation* and/or ice in the form of lenses, veins, or wedges and the like.

genesis, soil The mode of origin of the soil, with special reference to the processes responsible for the development of the solum, or true soil, from the unconsolidated parent material.

genetic horizon Soil layers that resulted from soil-forming (pedogenic) processes, as opposed to sedimentation or other geologic processes.

geographic information system (GIS) A method of overlaying, statistically analyzing, and integrating large volumes of spatial data of different kinds. The data are referenced to geographical coordinates and encoded in a form suitable for handling by computer.

geological erosion Wearing away of the Earth's surface by water, ice, or other natural agents under natural environmental conditions of climate, vegetation, and so on, undisturbed by man. Synonymous with *natural erosion*.

gibbsite, $Al(OH)_3$ An aluminum trihydroxide mineral most common in highly weathered soils, such as Oxisols.

gilgai The microrelief of soils produced by expansion and contraction with changes in moisture. Found in soils that contain large amounts of clay that swells and shrinks considerably with wetting and drying. Usually a succession of microbasins and microknolls in nearly level areas or of microvalleys and microridges parallel to the direction of the slope.

glacial drift Rock debris that has been transported by glaciers and deposited, either directly from the ice or from the meltwater. The debris may or may not be heterogeneous.

glacial till *See* till.

glaciofluvial deposits Material moved by glaciers and subsequently sorted and deposited by streams flowing from the melting ice. The deposits are stratified and may occur in the form of outwash plains, deltas, kames, eskers, and kame terraces.

gleyed A soil condition resulting from prolonged saturation with water and reducing conditions that manifest themselves in

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greenish or bluish colors throughout the soil mass or in mottles.

glomalin A protein-sugar group of molecules secreted by certain fungi resulting in a sticky hyphal surface thought to contribute to aggregate stability.

goethite, FeOOH A yellow-brown iron oxide mineral that accounts for the brown color in many soils.

granular structure Soil structure in which the individual grains are grouped into spherical aggregates with indistinct sides. Highly porous granules are commonly called *crumbs*. A well-granulated soil has the best structure for most ordinary crop plants. *See also* soil structure types.

granulation The process of producing granular materials. Commonly used to refer to the formation of soil structural granules, but also used to refer to the processing of powdery fertilizer materials into granules.

grassed waterway Broad and shallow channel, planted with grass (usually perennial species) that is designed to move surface water downslope without causing soil erosion.

gravitational potential That portion of the total *soil water potential* due to differences in elevation of the reference pool of pure water and that of the soil water. Since the soil water elevation is usually chosen to be higher than that of the reference pool, the gravitational potential is usually positive.

gravitational water Water that moves into, through, or out of the soil under the influence of gravity.

great group A category in *Soil Taxonomy*. The classes in this category contain soils that have the same kind of horizons in the same sequence and have similar moisture and temperature regimes.

green manure Plant material incorporated with the soil while green, or soon after maturity, for improving the soil.

greenhouse effect The entrapment of heat by upper atmosphere gases, such as carbon dioxide, water vapor, and methane, just as glass traps heat for a greenhouse. Increases in the quantities of these gases in the atmosphere will likely result in global warming that may have serious consequences for humankind.

groundwater Subsurface water in the zone of saturation that is free to move under the influence of gravity, often horizontally to stream channels.

grus A sediment or soil material comprised of loose grains of coarse sand and fine gravel size composed of quartz, feldspar and rock fragments. Produced from rocks by physical weathering or selectively transported by borrowing insects.

gully erosion The erosion process whereby water accumulates in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths, ranging from 1 to 2 ft to as much as 23 to 30 m (75 to 100 ft).

gypsic horizon A diagnostic subsurface horizon of secondary calcium sulfate enrichment that is more than 15 cm thick.

gypsum requirement The quantity of gypsum required to reduce the exchangeable sodium percentage in a soil to an acceptable level.

halophyte A plant that requires or tolerates a saline (high salt) environment.

hard armor Pertains to the use of hard materials (such as large stones or concrete) to prevent soil and stream bank erosion by reducing the erosive force of flowing water. *See* soft armor.

hardpan A hardened soil layer, in the lower A or in the B horizon, caused by cementation of soil particles with organic matter or with such materials as silica, sesquioxides, or calcium carbonate. The hardness does not change appreciably with changes in moisture content and pieces of the hard layer do not slake in water. *See also* caliche; claypan.

harrowing A secondary broadcast tillage operation that pulverizes, smooths, and firms the soil in seedbed preparation, controls weeds, or incorporates material spread on the surface.

heaving The partial lifting of plants, buildings, roadways, fenceposts, etc., out of the ground, as a result of freezing and thawing of the surface soil during the winter.

heavy metals Those metals that have densities of 5.0 Mg/m or greater. Elements in soils include Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Pb, and Zn.

heavy soil (Obsolete in scientific use) A soil with a high content of clay, and a high drawbar pull, hence difficult to cultivate.

hematite, Fe_2O_3 A red iron oxide mineral that contributes red color to many soils.

hemic material *See* organic materials.

herbicide A chemical that kills plants or inhibits their growth; intended for weed control.

herbivore A plant-eating animal.

heterotroph An organism capable of deriving energy for life processes only from the decomposition of organic compounds and incapable of using inorganic compounds as sole sources of energy or for organic synthesis. *Contrast with* autotroph.

histic epipedon A diagnostic surface horizon consisting of a thin layer of organic soil material that is saturated with water at some period of the year unless artificially drained and that is at or near the surface of a mineral soil.

Histosols An order in *Soil Taxonomy*. Soils formed from materials high in organic matter. Histosols with essentially no clay must have at least 20% organic matter by weight (about 78% by volume). This minimum organic matter content rises with increasing clay content to 30% (85% by volume) in soils with at least 60% clay.

horizon, soil A layer of soil, approximately parallel to the soil surface, differing in properties and characteristics from adjacent layers below or above it. *See also* diagnostic horizons.

horticulture The art and science of growing fruits, vegetables, and ornamental plants.

hue (color) *See* Munsell color system.

humic acid A mixture of dark colored organic substances produced by extraction of soil with strong alkali followed by precipitation in acid. Once thought to be a major constituent of soil organic matter.

humic substances A series of complex, high molecular weight, brown- to black-colored organic substances that occur in natural waters, sediments, and to a small extent in aerobic soils.

humid climate Climate in regions where water, when distributed normally throughout the year, should not limit crop production. In cool climates annual precipitation may be as little as 25 cm; in hot climates, 150 cm or even more. Forest is the common natural vegetation in uncultivated areas.

humification The processes involved in the decomposition and partial stabilization of organic matter and leading to the formation of humus.

humin Colloidal sized soil organic material that is not dissolved upon extraction of the soil with strong alkali. Part of an obsolete fractionation scheme for soil organic matter.

Humus: The portion of soil organic matter that is not alive or recognizable plant tissue, and is protected from rapid decomposition to some degree by the soil environment. It is generally colloidal in particle size and black in color. Previuously thought to be composed mainly of very large polymer molecules operationally defined as humic acids, folic acids and humin, which see.

hydration Chemical union between an ion or compound and one or more water molecules, the reaction being stimulated by the attraction of the ion or compound for either the hydrogen or the unshared electrons of the oxygen in the water.

hydraulic conductivity An expression of the readiness with which a liquid, such as water, flows through a solid, such as soil, in response to a given potential gradient.

hydric soils Soils that are water-saturated for long enough periods to produce reduced conditions and affect the growth of plants.

hydrogen bonding Relatively low energy bonding exhibited by a hydrogen atom located between two highly electronegative atoms, such as nitrogen or oxygen.

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hydrologic cycle The circuit of water movement from the atmosphere to the Earth and back to the atmosphere through various stages or processes, as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration.

hydrolysis A reaction with water that splits the water molecule into H^+ and OH^- ions. Molecules or atoms participating in such reactions are said to *hydrolyze*.

hydronium A hydrated hydrogen ion (H_3O^+), the form of the hydrogen ion usually found in an aqueous system.

hydroperiod The duration of the presence of surface water in seasonal wetlands.

hydroponics Plant-production systems that use nutrient solutions and no solid medium to grow plants.

hydrostatic potential *See* submergence potential.

hydrous mica *See* fine-grained mica.

hydroxyapatite A member of the apatite group of minerals rich in hydroxyl groups. A nearly insoluble calcium phosphate.

hygroscopic coefficient The amount of moisture in a dry soil when it is in equilibrium with some standard relative humidity near a saturated atmosphere (about 98%), expressed in terms of percentage on the basis of oven-dry soil.

hyperaccumulator A plant with unusually high capacity to take up certain elements from soil resulting in very high concentrations of these elements in the plant's tissues. Often pertaining to concentrations of heavy metals to 1% or more of the tissue dry matter.

hyperthermic A soil temperature class with mean annual temperatures >22 °C.

hypha (pl. hyphae) Filament of fungal cells. Actinomycetes also produce similar, but thinner, filaments of cells.

hypoxia State of oxygen deficiency in an environment so low as to restrict biological respiration (in water, typically less than 2 to 3 mg O_2/L).

hysteresis A relationship between two variables that changes depending on the sequences or starting point. An example is the relationship between soil water content and water potential, for which different curves describe the relationship when a soil is gaining water or losing it.

igneous rock Rock formed from the cooling and solidification of magma that has not been changed appreciably since its formation.

illite *See* fine-grained mica.

illuvial horizon A soil layer or horizon in which material carried from an overlying layer has been precipitated from solution or deposited from suspension. The layer of accumulation.

illuviation The process of deposition of soil material removed from one horizon to another in the soil; usually from an upper to a lower horizon in the soil profile. *See also* eluviation.

immature soil A soil with indistinct or only slightly developed horizons because of the relatively short time it has been subjected to the various soil-forming processes. A soil that has not reached equilibrium with its environment.

immobilization The conversion of an element from the inorganic to the organic form in microbial tissues or in plant tissues, thus rendering the element not readily available to other organisms or to plants.

imogolite A poorly crystalline aluminosilicate mineral with an approximate formula $SiO_2Al_2O_3 \cdot 2.5H_2O$; occurs mostly in soils formed from volcanic ash.

impervious Resistant to penetration by fluids or by roots.

improved fallow *See* fallow.

Inceptisols An order in *Soil Taxonomy*. Soils that are usually moist with pedogenic horizons of alteration of parent materials but not of illuviation. Generally, the direction of soil development is not yet evident from the marks left by various soil-forming processes or the marks are too weak to classify in another order.

induced systemic resistance Plant defense mechanisms activated by a chemical signal produced by a rhizosphere bacteria. Although the process begins in the soil, it may confer disease resistance to leaves or other aboveground tissues.

indurated (soil) Soil material cemented into a hard mass that will not soften on wetting. *See also* consistence; hardpan.

infiltration The downward entry of water into the soil.

infiltration capacity A soil characteristic determining or describing the *maximum* rate at which water *can* enter the soil under specified conditions, including the presence of an excess of water.

inner-sphere complex A relatively strong (not easily reversed) chemical association or bonding directly between a specific ion and specific atoms or groups of atoms in the surface structure of a soil colloid.

inoculation The process of introducing pure or mixed cultures of microorganisms into natural or artificial culture media.

inorganic compounds All chemical compounds in nature except compounds of carbon other than carbon monoxide, carbon dioxide, and carbonates.

insecticide A chemical that kills insects.

intergrade A soil that possesses moderately well-developed distinguishing characteristics of two or more genetically related great soil groups.

interlayer (mineralogy) Materials between layers within a given crystal, including cations, hydrated cations, organic molecules, and hydroxide groups or sheets.

internal surface The area of surface exposed within a clay crystal between the individual crystal layers. *Compare with* external surface.

interstratification Mixing of silicate layers within the structural framework of a given silicate clay.

ionic double layer The distribution of cations in the soil solution resulting from the simultaneous attraction toward colloid particles by the particle's negative charge and the tendency of diffusion and thermal forces to move the cations away from the colloid surfaces. Also described as a diffuse double layer or a diffuse electrical double layer.

ions Atoms, groups of atoms, or compounds that are electrically charged as a result of the loss of electrons (cations) or the gain of electrons (anions).

iron-pan An indurated soil horizon in which iron oxide is the principal cementing agent.

irrigation efficiency The ratio of the water actually consumed by crops on an irrigated area to the amount of water diverted from the source onto the area.

isomorphous substitution The replacement of one atom by another of similar size in a crystal lattice without disrupting or changing the crystal structure of the mineral.

isotopes Two or more atoms of the same element that have different atomic masses because of different numbers of neutrons in the nucleus.

joule The SI energy unit defined as a force of 1 newton applied over a distance of 1 meter; 1 joule = 0.239 calorie.

K_d *See* distribution coefficient, K_d.

K_{oc} The distribution coefficient, K_d, calculated based on organic carbon content. $K_{oc}=K_d/foc$ where foc is the fraction of organic carbon.

kame A conical hill or ridge of sand or gravel deposited in contact with glacial ice.

kandic horizon A subsurface diagnostic horizon having a sharp clay increase relative to overlying horizons and having low-activity clays.

kaolinite An aluminosilicate mineral of the 1:1 crystal lattice group; that is, consisting of single silicon tetrahedral sheets alternating with single aluminum octahedral sheets.

K_{sat} Hydraulic conductivity when the soil is water saturated. *See also* hydraulic conductivity.

k-strategist An organism that maintains a relatively stable population by specializing in metabolism of resistant compounds that most other organisms cannot utilize. *Contrast with* r-strategist. *See also* autochthonous organisms.

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labile A substance that is readily transformed by microorganisms or is readily available for uptake by plants.

lacustrine deposit Material deposited in lake water and later exposed either by lowering of the water level or by the elevation of the land.

land A broad term embodying the total natural environment of the areas of the Earth not covered by water. In addition to soil, its attributes include other physical conditions, such as mineral deposits and water supply; location in relation to centers of commerce, populations, and other land; the size of the individual tracts or holdings; and existing plant cover, works of improvement, and the like.

land capability classification A grouping of kinds of soil into special units, subclasses, and classes according to their capability for intensive use and the treatments required for sustained use. One such system has been prepared by the USDA Natural Resources Conservation Service.

land classification The arrangement of land units into various categories based upon the properties of the land or its suitability for some particular purpose.

land forming Shaping the surface of the land by scraping off the high spots and filling in the low spots with precision grading machinery to create a uniform, smooth slope, often for irrigation purposes. Also called *land smoothing*.

land-use planning The development of plans for the uses of land that, over long periods, will best serve the general welfare, together with the formulation of ways and means for achieving such uses.

laterite An iron-rich subsoil layer found in some highly weathered humid tropical soils that, when exposed and allowed to dry, becomes very hard and will not soften when rewetted. When erosion removes the overlying layers, the laterite is exposed and a virtual pavement results. *See also* plinthite.

layer (Clay mineralogy) A combination in silicate clays of (tetrahedral and octahedral) sheets in a 1:1, 2:1, or 2:1:1 combination.

leaching The removal of materials in solution from the soil by percolating waters. *See also* eluviation.

leaching requirement The leaching fraction of irrigation water necessary to keep soil salinity from exceeding a tolerance level of the crop to be grown.

leaf area index The ratio of the area of the total upper leaf surface of a plant canopy and the unit area on which the canopy is grown.

legume A pod-bearing member of the Leguminosae family, one of the most important and widely distributed plant families. Includes many valuable food and forage species, such as peas, beans, peanuts, clovers, alfalfas, sweet clovers, lespedezas, vetches, and kudzu. Nearly all legumes are associated with nitrogen-fixing organisms.

lichen A symbiotic relationship between fungi and cyanobacteria (blue-green algae) that enhances colonization of bare minerals and rocks. The fungi supply water and nutrients, the cyanobacteria the fixed nitrogen and carbohydrates from photosynthesis.

Liebig's law The growth and reproduction of an organism are determined by the nutrient substance (oxygen, carbon dioxide, calcium, etc.) that is available in minimum quantity with respect to organic needs; the *limiting factor*. Also attributed to Sprengel.

light soil (Obsolete in scientific use) A coarse-textured soil; a soil with a low drawbar pull and hence easy to cultivate. *See also* coarse texture; soil texture.

lignin The complex organic constituent of woody fibers in plant tissue that, along with cellulose, cements the cells together and provides strength. Lignins resist microbial attack and after some modification may become part of the soil organic matter.

lime (agricultural) In strict chemical terms, calcium oxide. In practical terms, a material containing the carbonates, oxides, and/or hydroxides of calcium and/or magnesium used to neutralize soil acidity.

lime requirement The mass of agricultural limestone, or the equivalent of other specified liming material, required to raise the pH of the soil to a desired value under field conditions.

limestone A sedimentary rock composed primarily of calcite ($CaCO_3$). If dolomite ($CaCO_3 \cdot MgCO_3$) is present in appreciable quantities, it is called a *dolomitic limestone*.

limiting factor *See* Liebig's law.

liquid limit (LL) *See* Atterberg limits.

lithosequence A group of related soils that differ, one from the other, in certain properties primarily as a result of parent material as a soil-forming factor.

loam The textural-class name for soil having a moderate amount of sand, silt, and clay. Loam soils contain 7 to 27% clay, 28 to 50% silt, and 23 to 52% sand.

loamy Intermediate in texture and properties between fine-textured and coarse-textured soils. Includes all textural classes with the words *loam* or *loamy* as a part of the class name, such as clay loam or loamy sand. *See also* loam; soil texture.

lodging Falling over of plants, either by uprooting or stem breakage.

loess Material transported and deposited by wind and consisting of predominantly silt-sized particles.

luxury consumption The intake by a plant of an essential nutrient in amounts exceeding what it needs. For example, if potassium is abundant in the soil, alfalfa may take in more than it requires.

lysimeter A device for measuring percolation (leaching) and evapotranspiration losses from a column of soil under controlled conditions.

macronutrient A chemical element necessary in large amounts (usually 50 mg/kg in the plant) for the growth of plants. Includes C, H, O, N, P, K, Ca, Mg, and S. (*Macro* refers to quantity and not to the essentiality of the element.) *See also* micronutrient.

macropores Larger soil pores, generally having a diameter greater than 0.08 mm, from which water drains readily by gravity.

map unit (mapping unit), soil A conceptual group of one to many component soils, delineated or identified by the same name in a soil survey, that represent similar landscape areas. *See also* delineation, soil consociation, soil complex, soil association, and undifferentiated group.

marl Soft and unconsolidated calcium carbonate, usually mixed with varying amounts of clay or other impurities.

marsh Periodically wet or continually flooded area with the surface not deeply submerged. Covered dominantly with sedges, cattails, rushes, or other hydrophytic plants. Subclasses include freshwater and saltwater marshes.

mass flow Movement of nutrients with the flow of water to plant roots.

matric potential That portion of the total *soil water potential* due to the attractive forces between water and soil solids as represented through adsorption and capillarity. It will always be negative.

mature soil A soil with well-developed soil horizons produced by the natural processes of soil formation and essentially in equilibrium with its present environment.

maximum retentive capacity The average moisture content of a disturbed sample of soil, 1 cm high, which is at equilibrium with a water table at its lower surface.

mechanical analysis (Obsolete) *See* particle size analysis; particle size distribution.

medium texture Intermediate between fine-textured and coarse-textured (soils). It includes the following textural classes: very fine sandy loam, loam, silt loam, and silt.

melanic epipedon A diagnostic surface horizon formed in volcanic parent material that contains more than 6% organic carbon, is dark in color, and has a very low bulk density and high anion adsorption capacity.

mellow soil A very soft, very friable, porous soil without any tendency toward hardness or harshness. *See also* consistence.

mesic A soil temperature class with mean annual temperature 8 to 15 °C.

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mesofauna Animals of medium size, between approximately 2 and 0.2 mm in diameter.

mesophilic Pertaining to moderate temperatures in the range of 15 to 35 °C, the range in which mesophilic organisms grow best and in which mesophilic composting takes place.

metamorphic rock A rock that has been greatly altered from its previous condition through the combined action of heat and pressure. For example, marble is a metamorphic rock produced from limestone, gneiss is produced from granite, and slate is produced from shale.

methane, CH_4 An odorless, colorless gas commonly produced under anaerobic conditions. When released to the upper atmosphere, methane contributes to global warming. *See also* greenhouse effect.

micas Primary aluminosilicate minerals in which two silica tetrahedral sheets alternate with one alumina/magnesia octahedral sheet with entrapped potassium atoms fitting between sheets. They separate readily into visible sheets or flakes.

microfauna That part of the animal population which consists of individuals too small to be clearly distinguished without the use of a microscope. Includes protozoans and nematodes.

microflora That part of the plant population which consists of individuals too small to be clearly distinguished without the use of a microscope. Includes actinomycetes, algae, bacteria, and fungi.

micronutrient A chemical element necessary in only extremely small amounts (<50 mg/kg in the plant) for the growth of plants. Examples are B, Cl, Cu, Fe, Mn, and Zn. (*Micro* refers to the amount used rather than to its essentiality.) *See also* macronutrient.

micropores Relatively small soil pores, generally found within structural aggregates and having a diameter less than 0.08 mm. *Contrast to* macropores.

microrelief Small-scale local differences in topography, including mounds, swales, or pits that are only 1 m or so in diameter and with elevation differences of up to 2 m. *See also* gilgai.

mineral (i) An inorganic compound of defined composition found in rocks. (ii) An adjective meaning inorganic.

mineral nutrient An element in inorganic form used by plants or animals.

mineral soil A soil consisting predominantly of, and having its properties determined predominantly by, mineral matter. Usually contains <20% organic matter, but may contain an organic surface layer up to 30 cm thick.

mineralization The conversion of an element from an organic form to an inorganic state as a result of microbial decomposition.

minimum tillage *See* tillage, conservation.

minor element (Obsolete) *See* micronutrient.

moderately coarse texture Consisting predominantly of coarse particles. In soil textural classification, it includes all the sandy loams except the very fine sandy loam. *See also* coarse texture.

moderately fine texture Consisting predominantly of intermediate-sized (soil) particles or with relatively small amounts of fine or coarse particles. In soil textural classification, it includes clay loam, sandy loam, sandy clay loam, and silty clay loam. *See also* fine texture.

moisture potential *See* soil water potential.

mole drain Unlined drain formed by pulling a bullet-shaped cylinder through the soil.

mollic epipedon A diagnostic surface horizon of mineral soil that is dark colored and relatively thick, contains at least 0.6% organic carbon, is not massive and hard when dry, has a base saturation of more than 50%, has less than 250 mg/kg P_2O_5 soluble in 1% citric acid, and is dominantly saturated with bivalent cations.

Mollisols An order in *Soil Taxonomy*. Soils with nearly black, organic-rich surface horizons and high supply of bases. They have mollic epipedons and base saturation greater than 50% in any cambic or argillic horizon. They lack the characteristics of Vertisols and must not have oxic or spodic horizons.

molybdenosis A nutritional disease of ruminant animals in which high Mo in the forage interferes with copper absorption.

montmorillonite An aluminosilicate clay mineral in the smectite group with a 2:1 expanding crystal lattice, with two silicon tetrahedral sheets enclosing an aluminum octahedral sheet. Isomorphous substitution of magnesium for some of the aluminum has occurred in the octahedral sheet. Considerable expansion may be caused by water moving between silica sheets of contiguous layers.

mor Raw humus; type of forest humus layer of unincorporated organic material, usually matted or compacted or both; distinct from the mineral soil, unless the latter has been blackened by washing in organic matter.

moraine An accumulation of drift, with an initial topographic expression of its own, built within a glaciated region chiefly by the direct action of glacial ice. Examples are ground, lateral, recessional, and terminal moraines.

morphology, soil The constitution of the soil, including the texture, structure, consistence, color, and other physical, chemical, and biological properties of the various soil horizons that make up the soil profile.

mottling Spots or blotches of different color or shades of color interspersed with the dominant color.

mucigel The gelatinous material at the surface of roots grown in unsterilized soil.

muck Highly decomposed organic material in which the original plant parts are not recognizable. Contains more mineral matter and is usually darker in color than peat. *See also* muck soil; peat.

muck soil (1) A soil containing 20 to 50% organic matter. (2) An organic soil in which the organic matter is well decomposed.

mulch Any material such as straw, sawdust, leaves, plastic film, and loose soil that is spread upon the surface of the soil to protect the soil and plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc.

mulch tillage *See* tillage, conservation.

mull A humus-rich layer of forested soils consisting of mixed organic and mineral matter. A mull blends into the upper mineral layers without an abrupt change in soil characteristics.

Munsell color system A color designation system that specifies the relative degrees of the three simple variables of color:

- **chroma** The relative purity, strength, or saturation of a color.
- **hue** The chromatic gradation (rainbow) of light that reaches the eye.
- **value** The degree of lightness or darkness of the color.

mycelium A stringlike mass of individual fungal or actinomycetes hyphae.

myco Prefix designating an association or relationship with a fungus (e.g., mycotoxins are toxins produced by a fungus).

mycorrhiza The association, usually symbiotic, of fungi with the roots of seed plants. *See also* ectotrophic mycorrhiza; endotrophic mycorrhiza; arbuscular mycorrhiza.

natric horizon A diagnostic subsurface horizon that satisfies the requirements of an argillic horizon, but that also has prismatic, columnar, or blocky structure and a subhorizon having more than 15% saturation with exchangeable sodium.

necrosis Death associated with discoloration and dehydration of all or parts of plant organs, such as leaves.

nematodes Very small (most are microscopic) unsegmented round worms. In soils they are abundant and perform many important functions in the soil food web. Some are plant parasites and considered pests.

neutral soil A soil in which the surface layer, at least to normal plow depth, is neither acid nor alkaline in reaction. In practice this means the soil is within the pH range of 6.6 to 7.3. *See also* acid soil; alkaline soil; pH; reaction, soil.

nitrate depression period A period of time, beginning shortly after the addition of

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fresh, highly carbonaceous organic materials to a soil, during which decomposer microorganisms have removed most of the soluble nitrate from the soil solution.

nitrification The biochemical oxidation of ammonium to nitrate, predominantly by autotrophic bacteria.

nitrogen assimilation The incorporation of nitrogen into organic cell substances by living organisms.

nitrogen cycle The sequence of chemical and biological changes undergone by nitrogen as it moves from the atmosphere into water, soil, and living organisms, and upon death of these organisms (plants and animals) is recycled through a part or all of the entire process.

nitrogen fixation The biological conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilized in biological processes.

nodule bacteria *See* rhizobia.

nonacid cations Those cations that do not react with water by hydrolysis to release H^+ ions to the soil solution. These cations do not remove hydroxyl ions from solution, but form strongly dissociated bases such as potassium hydroxide ($K^+ + OH$). Formerly called *base cations* or *base-forming cations* in soil science literature.

nonacid saturation The proportion or percentage of a cation-exchange site occupied by nonacid cations. Formerly termed *base saturation*.

nonhumic substances The portion of soil organic matter comprised of relatively low molecular weight organic substances; mostly identifiable biomolecules.

nonlimiting water range The region bounded by the upper and lower soil water content over which water, oxygen, and mechanical resistance are not limiting to plant growth. *Compare with* available water.

nonpoint source A pollution source that cannot be traced back to a single origin or source. Examples include water runoff from urban areas and leaching from croplands.

no-tillage *See* tillage, conservation.

nucleic acids Complex organic acids found in the nuclei of plant and animal cells; may be combined with proteins as nucleoproteins.

O horizon Organic horizon of mineral soils.

ochric epipedon A diagnostic surface horizon of mineral soil that is too light in color, too high in chroma, too low in organic carbon, or too thin to be a plaggen, mollic, umbric, anthropic, or histic epipedon, or that is both hard and massive when dry.

octahedral sheet Sheet of horizontally linked, octahedral-shaped units that serve as the basic structural components of silicate (clay) minerals. Each unit consists of a central, six-coordinated metallic atom (e.g., Al, Mg, or Fe) surrounded by six hydroxyl groups that, in turn, are linked with other nearby metal atoms, thereby serving as interunit linkages that hold the sheet together.

oligotrophic Environments, such as soils or lakes, which are poor in nutrients.

order, soil The category at the highest level of generalization in *Soil Taxonomy*. The properties selected to distinguish the orders are reflections of the degree of horizon development and the kinds of horizons present.

organic farming A system/philosophy of agriculture that does not allow the use of synthetic chemicals to produce plant and animal products, but instead emphasizes the management of soil organic matter and biological processes. In many countries, products are officially certified as being organic if inspections confirm that they were grown by these methods.

organic fertilizer By-product from the processing of animal or vegetable substances that contain sufficient plant nutrients to be of value as fertilizers.

organic soil A soil in which more than half of the profile thickness is comprised of organic soil materials.

organic soil materials (As used in *Soil Taxonomy*): (1) Saturated with water for prolonged periods unless artificially drained and having 18% or more organic carbon (by weight) if the mineral fraction is more than 60% clay, more than 12% organic carbon if the mineral fraction has no clay, or between 12 and 18% carbon if the clay content of the mineral fraction is between 0 and 60%. (2) Never saturated with water for more than a few days and having more than 20% organic carbon. Histosols develop on these organic soil materials. There are three kinds of organic materials:

- **fibric materials** The least decomposed of all the organic soil materials, containing very high amounts of fiber that are well preserved and readily identifiable as to botanical origin; with very low bulk density.
- **hemic materials** Intermediate in degree of decomposition of organic materials between the less decomposed fibric and the more decomposed sapric materials.
- **sapric materials** The most highly decomposed of the organic materials, having the highest bulk density, least amount of plant fiber, and lowest water content at saturation.

orographic Influenced by mountains (Greek *oros*). Used in reference to increased precipitation on the windward side of a mountain range induced as clouds rise over the mountain, leaving a *rain shadow* of reduced precipitation on the leeward side.

ortstein An indurated layer in the B horizon of Spodosols in which the cementing material consists of illuviated sesquioxides (mostly iron) and organic matter.

osmotic potential That portion of the total *soil water potential* due to the presence of solutes in soil water. It will generally be negative.

osmotic pressure Pressure exerted in living bodies as a result of unequal concentrations of salts on both sides of a cell wall or membrane. Water moves from the area having the lower salt concentration through the membrane into the area having the higher salt concentration and, therefore, exerts additional pressure on the side with higher salt concentration.

outer-sphere complex A relatively weak (easily reversed) chemical association or general attraction between an ion and an oppositely charged soil colloid via mutual attraction for intervening water molecules.

outwash plain A deposit of coarse-textured materials (e.g., sands and gravels) left by streams of meltwater flowing from receding glaciers.

oven-dry soil Soil that has been dried at 105 °C until it reaches constant weight.

oxic horizon A diagnostic subsurface horizon that is at least 30 cm thick and is characterized by the virtual *absence* of weatherable primary minerals or 2:1 lattice clays and the *presence* of 1:1 lattice clays and highly insoluble minerals, such as quartz sand, hydrated oxides of iron and aluminum, low cation exchange capacity, and small amounts of exchangeable bases.

oxidation The loss of electrons by a substance; therefore, a gain in positive valence charge and, in some cases, the chemical combination with oxygen gas.

oxidation ditch An artificial open channel for partial digestion of liquid organic wastes in which the wastes are circulated and aerated by a mechanical device.

oxidation-reduction potential *See* E_h and pe.

Oxisols An order in *Soil Taxonomy*. Soils with residual accumulations of low-activity clays, free oxides, kaolin, and quartz. They are mostly in tropical climates.

pans Horizons or layers in soils that are strongly compacted, indurated, or very high in clay content. *See also* caliche; claypan; fragipan; hardpan.

parent material The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of soils is developed by pedogenic processes.

particle density The mass per unit volume of the soil particles. In technical work, usually expressed as metric tons per cubic meter (Mg/m^3) or grams per cubic centimeter (g/cm^3).

particle size The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

particle size analysis Determination of the various amounts of the different separates in

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a soil sample, usually by sedimentation, sieving, micrometry, or combinations of these methods.

particle size distribution The amounts of the various soil separates in a soil sample, usually expressed as weight percentages.

particulate organic matter A microbially active fraction of soil organic matter consisting largely of fine particles of partially decomposed plant tissue.

partitioning The distribution of organic chemicals (such as pollutants) into a portion that dissolves in the soil organic matter and a portion that remains undissolved in the soil solution.

pascal An SI unit of pressure equal to 1 newton per square meter.

peat Unconsolidated soil material consisting largely of undecomposed, or only slightly decomposed, organic matter accumulated under conditions of excessive moisture. *See also* organic soil materials; peat soil.

peat soil An organic soil containing more than 50% organic matter. Used in the United States to refer to the stage of decomposition of the organic matter, *peat* referring to the slightly decomposed or undecomposed deposits and *muck* to the highly decomposed materials. *See also* muck; muck soil; peat.

ped A unit of soil structure such as an aggregate, crumb, prism, block, or granule, formed by natural processes (in contrast to a *clod*, which is formed artificially).

pedology The science that deals with the formation, morphology, and classification of soil bodies as landscape components.

pedon The smallest volume that can be called *a soil*. It has three dimensions. It extends downward to the depth of plant roots or to the lower limit of the genetic soil horizons. Its lateral cross section is roughly hexagonal and ranges from 1 to 10 m^2 in size, depending on the variability in the horizons.

pedosphere The conceptual zone within the ecosystem consisting of soil bodies or directly influenced by them. A zone or sphere of activity in which mineral, water, air, and biological components come together to form soils. Usage is parallel to that for "atmosphere" or "biosphere."

pedoturbation Physical disturbance and mixing of soil horizons by such forces as burrowing animals (faunal pedoturbation) or frost churning (cryoturbation).

peneplain A once high, rugged area that has been reduced by erosion to a lower, gently rolling surface resembling a plain.

penetrability The ease with which a probe can be pushed into the soil. May be expressed in units of distance, speed, force, or work depending on the type of penetrometer used.

penetrometer An instrument consisting of a rod with a cone-shaped tip and a means of measuring the force required to push the rod into a specified increment of soil.

perc test *See* percolation test.

percolation, soil water The downward movement of water through soil. Especially, the downward flow of water in saturated or nearly saturated soil at hydraulic gradients of the order of 1.0 or less.

percolation test A measurement of the rate of percolation of water in a soil profile, usually to determine the suitability of a soil for use as a septic tank drain field.

perforated plastic pipe Pipe, sometimes flexible, with holes or slits in it that allow the entrance and exit of air and water. Used for soil drainage and for septic effluent spreading into soil.

permafrost (1) Permanently frozen material underlying the solum. (2) A perennially frozen soil horizon.

permanent charge *See* constant charge.

permanent wilting point *See* wilting point.

permeability, soil The ease with which gases, liquids, or plant roots penetrate or pass through a bulk mass of soil or a layer of soil.

petrocalcic horizon A diagnostic subsurface horizon that is a continuous, indurated calcic horizon cemented by calcium carbonate and, in some places, with magnesium carbonate. It cannot be penetrated with a spade or auger when dry; dry fragments do not slake in water; and it is impenetrable by roots.

petrogypsic horizon A diagnostic subsurface horizon that is a continuous, strongly cemented, massive gypsic horizon that is cemented by calcium sulfate. It can be chipped with a spade when dry. Dry fragments do not slake in water and it is impenetrable by roots.

pH, soil The negative logarithm of the hydrogen ion activity (concentration) of a soil. The degree of acidity (or alkalinity) of a soil as determined by means of a glass or other suitable electrode or indicator at a specified moisture content or soil-to-water ratio, and expressed in terms of the pH scale.

pH-dependent charge That portion of the total charge of the soil particles that is affected by, and varies with, changes in pH.

phase, soil A subdivision of a soil series or other unit of classification having characteristics that affect the use and management of the soil but do not vary sufficiently to differentiate it as a separate series. Included are such characteristics as degree of slope, degree of erosion, and content of stones.

photomap A mosaic map made from aerial photographs to which place names, marginal data, and other map information have been added.

phyllosphere The leaf surface.

physical properties (of soils) Those characteristics, processes, or reactions of a soil that are caused by physical forces and that can be described by, or expressed in, physical terms or equations. Examples of physical properties are bulk density, water-holding capacity, hydraulic conductivity, porosity, pore-size distribution, and so on.

physical weathering The breakdown of rock and mineral particles into smaller particles by physical forces such as frost action. *See also* weathering.

phytoliths Biologically deposited silica (SiO_2) or mineral bodies (biogenic opal) created by plants and comprising the predominant form if silica in most plant tissue.

phytotoxic substances Chemicals that are toxic to plants.

placic horizon A diagnostic subsurface horizon of a black to dark reddish mineral soil that is usually thin but that may range from 1 to 25 mm in thickness. The placic horizon is commonly cemented with iron and is slowly permeable or impenetrable to water and roots.

plaggen epipedon A diagnostic surface horizon that is human-made and more than 50 cm thick. Formed by long-continued manuring and mixing.

plant nutrients *See* essential element.

plastic limit (PL) *See* Atterberg limits.

plastic soil A soil capable of being molded or deformed continuously and permanently, by relatively moderate pressure, into various shapes. *See also* consistence.

platy Consisting of soil aggregates that are developed predominantly along the horizontal axes; laminated; flaky.

plinthite (brick) A highly weathered mixture of sesquioxides of iron and aluminum with quartz and other diluents that occurs as red mottles and that changes irreversibly to hardpan upon alternate wetting and drying.

plow layer The soil ordinarily moved when land is plowed; equivalent to *surface soil*.

plow pan A subsurface soil layer having a higher bulk density and lower total porosity than layers above or below it, as a result of pressure applied by normal plowing and other tillage operations.

plowing A primary broad-base tillage operation that is performed to shatter soil uniformly with partial to complete inversion.

point of zero charge The pH value of a solution in equilibrium with a particle whose net charge, from all sources, is zero.

point source A pollution source that can be traced back to its origin, which is usually an effluent discharge pipe. Examples are a wastewater treatment plant or a factory. *Opposite of* nonpoint source.

polypedon (As used in *Soil Taxonomy*) Two or more contiguous pedons, all of which are within the defined limits of a single soil series; commonly referred to as a *soil individual*.

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pool A portion of a larger store of a substance defined by kinetic or theoretical properties. For example, the active pool of soil organic matter is defined by its rapid rate of microbial turnover. *Compare to* fraction.

pore size distribution The volume of the various sizes of pores in a soil. Expressed as percentages of the bulk volume (soil plus pore space).

porosity, soil The volume percentage of the total soil bulk not occupied by solid particles.

potential acidity The acidity that could potentially be formed if reduced sulfur compounds in a potential acid sulfate soil were to become oxidized.

precision farming The spatially variable management of a field or farm based on information specific to the soil or crop characteristics of many very small subunits of land. This technique commonly uses variable rate equipment, geo positioning systems and computer controls.

preferential flow Nonuniform movement of water and its solutes through a soil along certain pathways, which are often macropores.

primary consumer An organism that subsists on plant material.

primary mineral A mineral that has not been altered chemically since deposition and crystallization from molten lava.

primary producer An organism (usually a photosynthetic plant) that creates organic, energy-rich material from inorganic chemicals, solar energy, and water.

primary tillage *See* tillage, primary.

priming effect The increased decomposition of relatively stable, protected soil humus under the influence of much enhanced, generally biological, activity resulting from the addition of fresh organic materials to a soil.

prismatic soil structure A soil structure type with prismlike aggregates that have a vertical axis much longer than the horizontal axes.

Proctor test A laboratory procedure that indicates the maximum achievable bulk density for a soil and the optimum water content for compacting a soil.

productivity, soil The capacity of a soil for producing a specified plant or sequence of plants under a specified system of management. Productivity emphasizes the capacity of soil to produce crops and should be expressed in terms of yields.

profile, soil A vertical section of the soil through all its horizons and extending into the parent material.

prokaryote An organism whose cells do not have a distinct nucleus.

protein Any of a group of nitrogen-containing organic compounds formed by the polymerization of a large number of amino acid molecules and that, upon hydrolysis, yield these amino acids. They are essential parts of living matter and are one of the essential food substances of animals.

protonation Attachment of protons (H^+ ions) to exposed OH groups on the surface of soil particles, resulting in an overall positive charge on the particle surface.

protozoa One-celled eukaryotic organisms, such as amoeba.

puddled soil Dense, massive soil artificially compacted when wet and having no aggregated structure. The condition commonly results from the tillage of a clayey soil when it is wet.

rain, acid *See* acid rain.

reaction, soil (No longer used in soil science) The degree of acidity or alkalinity of a soil, usually expressed as a pH value or by terms ranging from extremely acid for pH values <4.5 to very strongly alkaline for pH values >9.0.

reactive nitrogen All forms of nitrogen that are readily available to biota (mainly ammonia, ammonium, and nitrate with smaller quantities of other compounds including nitrogen oxide gases) as opposed to unreactive nitrogen that exists mostly as inert N_2 gas.

recharge area A geographic area in which an otherwise confined aquifer is exposed to surficial percolation of water to recharge the groundwater in the aquifer.

redox concentrations Zones of apparent accumulations of Fe-Mn oxides in soils.

redox depletions Zones of low chroma (<2) where Fe-Mn oxides, and in some cases clay, have been stripped from the soil.

redox potential The electrical potential (measured in volts or millivolts) of a system due to the tendency of the substances in it to give up or acquire electrons.

redoximorphic features Soil properties associated with wetness that result from reduction and oxidation of iron and manganese compounds after saturation and desaturation with water. *See also* redox concentrations; redox depletions.

reduction The gain of electrons, and therefore the loss of positive valence charge, by a substance. In some cases, a loss of oxygen or a gain of hydrogen is also involved.

regolith The unconsolidated mantle of weathered rock and soil material on the Earth's surface; loose earth materials above solid rock. (Approximately equivalent to the term *soil* as used by many engineers.)

relief The relative differences in elevation between the upland summits and the lowlands or valleys of a given region.

residual material Unconsolidated and partly weathered mineral materials accumulated by disintegration of consolidated rock in place.

resilience The capacity of a soil (or other ecosystem) to return to its original state after a disturbance.

rhizobacteria Bacteria specially adapted to colonizing the surface of plant roots and the soil immediately around plant roots. Some have effects that promote plant growth, while others have effects that are deleterious to plants.

rhizobia Bacteria capable of living symbiotically with higher plants, usually in nodules on the roots of legumes, from which they receive their energy, and capable of converting atmospheric nitrogen to combined organic forms; hence the term *symbiotic nitrogen-fixing bacteria*. (Derived from the generic name *Rhizobium*.)

rhizoplane The root surface–soil interface. Used to describe the habitat of root-surface-dwelling microorganisms.

rhizosphere That portion of the soil in the immediate vicinity of plant roots in which the abundance and composition of the microbial population are influenced by the presence of roots.

rill A small, intermittent water course with steep sides; usually only a few centimeters deep and hence no obstacle to tillage operations.

rill erosion An erosion process in which numerous small channels of only several centimeters in depth are formed; occurs mainly on recently cultivated soils. *See also* rill.

riparian zone The area, both above and below the ground surface, that borders a river.

riprap Coarse rock fragments, stones, or boulders placed along a waterway or hillside to prevent erosion.

rock The material that forms the essential part of the earth's solid crust, including loose incoherent masses such as sand and gravel, as well as solid masses of granite and limestone.

root interception Acquisition of nutrients by a root as a result of the root growing into the vicinity of the nutrient source.

root nodules Swollen growths on plant roots. Often in reference to those in which symbiotic microorganisms live.

rotary tillage *See* tillage, rotary.

r-strategist Opportunistic organisms with short reproductive times that allow them to respond rapidly to the presence of easily metabolized food sources. *Contrast with* k-strategist. *See also* zymogenous organisms.

runoff The portion of the precipitation on an area that is discharged from the area through stream channels. That which is lost without entering the soil is called *surface runoff* and that which enters the soil before reaching the stream is called *groundwater runoff* or *seepage flow* from groundwater. (In soil science *runoff* usually refers to the water lost by surface flow; in geology and hydraulics *runoff*

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usually includes both surface and subsurface flow.)

salic horizon A diagnostic subsurface horizon of enrichment with secondary salts more soluble in cold water than gypsum. A salic horizon is 15 cm or more in thickness.

saline seep An area of land in which saline water seeps to the surface, leaving a high salt concentration behind as the water evaporates.

saline soil A nonsodic soil containing sufficient soluble salts to impair its productivity. The conductivity of a saturated extract is >4 dS/m, the exchangeable sodium adsorption ratio is less than about 13, and the pH is <8.5.

saline-sodic soil A soil containing sufficient exchangeable sodium to interfere with the growth of most crop plants and containing appreciable quantities of soluble salts. The exchangeable sodium adsorption ratio is >13, the conductivity of the saturation extract is >4 dS/m (at 25 °C), and the pH is usually 8.5 or less in the saturated soil.

salinization The process of accumulation of salts in soil.

saltation Particle movement in water or wind where particles skip or bounce along the stream bed or soil surface.

sand A soil particle between 0.05 and 2.0 mm in diameter; a soil textural class.

sapric materials *See* organic soil materials.

saprolite Soft, friable, weathered bedrock that retains the fabric and structure of the parent rock but is porous and can be dug with a spade.

saprophyte An organism that lives on dead organic material.

saturated paste extract The extract from a saturated soil paste, the electrical conductivity *E*c of which gives an indirect measure of salt content in a soil.

saturation extract The solution extracted from a saturated soil paste.

saturation percentage The water content of a saturated soil paste, expressed as a dry weight percentage.

savanna (savannah) A grassland with scattered trees, either as individuals or clumps. Often a transitional type between true grassland and forest.

second bottom The first terrace above the normal floodplain of a stream.

secondary mineral A mineral resulting from the decomposition of a primary mineral or from the reprecipitation of the products of decomposition of a primary mineral. *See also* primary mineral.

sediment Transported and deposited particles or aggregates derived from soils, rocks, or biological materials.

sedimentary rock A rock formed from materials deposited from suspension or precipitated from solution and usually being more or less consolidated. The principal sedimentary rocks are sandstones, shales, limestones, and conglomerates.

seedbed The soil prepared to promote the germination of seed and the growth of seedlings.

self-mulching soil A soil in which the surface layer becomes so well aggregated that it does not crust and seal under the impact of rain but instead serves as a surface mulch upon drying.

semiarid Term applied to regions or climates where moisture is more plentiful than in arid regions but still definitely limits the growth of most crop plants. Natural vegetation in uncultivated areas is short grasses.

separate, soil One of the individual-sized groups of mineral soil particles—sand, silt, or clay.

septic tank An underground tank used in the deposition of domestic wastes. Organic matter decomposes in the tank, and the effluent is drained into the surrounding soil.

series, soil The soil series is a subdivision of a family in *Soil Taxonomy* and consists of soils that are similar in all major profile characteristics.

sewage effluent The liquid part of sewage or wastewater; it is usually treated to remove some portion of the dissolved organic compounds and nutrients present from the original sewage.

sewage sludge Settled sewage solids combined with varying amounts of water and dissolved materials, removed from sewage by screening, sedimentation, chemical precipitation, or bacterial digestion. Also called *biosolids* if certain quality standards are met.

shear Force, as of a tillage implement, acting at right angles to the direction of movement.

sheet (Mineralogy) A flat array of more than one atomic thickness and composed of one or more levels of linked coordination polyhedra. A sheet is thicker than a plane and thinner than a layer. Examples: tetrahedral sheet, octahedral sheet.

sheet erosion The removal of a fairly uniform layer of soil from the land surface by runoff water.

shelterbelt A wind barrier of living trees and shrubs established and maintained for protection of farm fields. Syn. *windbreak*.

shifting cultivation A farming system in which land is cleared, the debris burned, and crops grown for 2 to 3 years. When the farmer moves on to another plot, the land is then left idle for 5 to 15 years; then the burning and planting process is repeated.

short-range order minerals Minerals, such as allophane, whose structural framework consists of short distances of well-ordered crystalline structure interspersed with distances of noncrystalline amorphous materials.

shrinkage limit (SL) The water content above which a mass of soil material will swell in volume, but below which it will shrink no further.

side-dressing The application of fertilizer alongside row-crop plants, usually on the soil surface. Nitrogen materials are most commonly side-dressed.

siderophore A nonporphyrin metabolite secreted by certain microorganisms that forms a highly stable coordination compound with iron.

silica/alumina ratio The molecules of silicon dioxide (SiO_2) per molecule of aluminum oxide (Al_2O_3) in clay minerals or in soils.

silica/sesquioxide ratio The molecules of silicon dioxide (SiO_2) per molecule of aluminum oxide (Al_2O_3) plus ferric oxide (Fe_2O_3) in clay minerals or in soils.

silt (1) A soil separate consisting of particles between 0.05 and 0.002 mm in equivalent diameter. (2) A soil textural class.

silting The deposition of waterborne sediments in stream channels, lakes, reservoirs, or on floodplains, usually resulting from a decrease in the velocity of the water.

site index A quantitative evaluation of the productivity of a soil for forest growth under the existing or specified environment.

slag A product of smelting, containing mostly silicates; the substances not sought to be produced as matte or metal and having a lower specific gravity.

slash-and-burn *See* shifting cultivation.

slick spots Small areas in a field that are slick when wet because of a high content of alkali or exchangeable sodium.

slickensides Stress surfaces that are polished and striated and are produced by one mass sliding past another.

slope The degree of deviation of a surface from horizontal, measured in a numerical ratio, percent, or degrees.

slow fraction (of soil organic matter) That portion of soil organic matter that can be metabolized with great difficulty by the microorganisms in the soil and therefore has a slow turnover rate with a half-life in the soil ranging from a few years to a few decades. Often this fraction is the product of some previous decomposition.

smectite A group of silicate clays having a 2:1-type lattice structure with sufficient isomorphous substitution in either or both the tetrahedral and octahedral sheets to give a high interlayer negative charge and high cation exchange capacity and to permit significant interlayer expansion and consequent shrinking and swelling of the clay. Montmorillonite, beidellite, and saponite are in the smectite group.

sodic soil A soil that contains sufficient sodium to interfere with the growth of most

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crop plants, and in which the sodium adsorption ratio is 13 or greater.

sodium adsorption ratio (SAR)

$$SAR = \frac{[Na^+]}{\sqrt{1/2([Ca^{2+}] + [Mg^{2+}])}}$$

where the cation concentrations are in millimoles of charge per liter ($mmol_c/L$).

soft armor The bioengineering use of organic and/or inorganic materials combined with plants to create a living vegetation barrier of protection against erosion.

soil (1) A dynamic natural body composed of mineral and organic solids, gases, liquids and living organisms which can serve as a medium for plant growth. (2) The collection of natural bodies occupying parts of the Earth's surface that is capable of supporting plant growth and that has properties resulting from the integrated effects of climate and living organisms acting upon parent material, as conditioned by topography, over periods of time.

soil air The soil atmosphere; the gaseous phase of the soil, being that volume not occupied by soil or liquid.

soil alkalinity The degree or intensity of alkalinity of a soil, expressed by a value >7.0 on the pH scale.

soil amendment Any material, such as lime, gypsum, sawdust, or synthetic conditioner, that is worked into the soil to make it more amenable to plant growth.

soil association A group of defined and named taxonomic soil units occurring together in an individual and characteristic pattern over a geographic region, comparable to plant associations in many ways.

soil auger A tool used to bore small holes up to several meters deep in soils in order to bring up samples of material from various soil layers. It consists of a long T-handle attached to either a cylinder with twisted teeth or a screwlike bit.

soil classification (Soil Taxonomy) The systematic arrangement of soils into groups or categories on the basis of their characteristics. *See* order; suborder; great group; subgroup; family; and series.

soil complex A mapping unit used in detailed soil surveys where two or more defined taxonomic units are so intimately intermixed geographically that it is undesirable or impractical, because of the scale being used, to separate them. A more intimate mixing of smaller areas of individual taxonomic units than that described under *soil association*.

soil compressibility The property of a soil pertaining to its capacity to decrease in bulk volume when subjected to a load.

soil conditioner Any material added to a soil for the purpose of improving its physical condition.

soil conservation A combination of all management and land-use methods that safeguard the soil against depletion or deterioration caused by nature and/or humans.

soil consociation A kind of soil map unit that is named for the dominant soil taxon in the delineation, and in which at least half of the pedons are of the named soil taxon, and most of the remaining pedons are so similar as to not affect most interpretations.

soil correlation The process of defining, mapping, naming, and classifying the kinds of soils in a specific soil survey area, the purpose being to ensure that soils are adequately defined, accurately mapped, and uniformly named.

soil erosion *See* erosion.

soil fertility *See* fertility, soil.

soil genesis *See* genesis, soil.

soil geography A subspecialization of physical geography concerned with the areal distributions of soil types.

soil health The state of self-regulation, stability, resilience, and lack of stress symptoms in a soil as an ecosystem of living organisms that supports the growth of plants. Sometimes used synonymously with soil quality, but usually focused on the plant growth supporting function of soil.

soil horizon *See* horizon, soil.

soil loss tolerance (T value) (i) The maximum average annual soil loss that will allow continuous cropping and maintain soil productivity without requiring additional management inputs. (ii) The maximum soil erosion loss that is offset by the theoretical maximum rate of soil development, which will maintain an equilibrium between soil losses and gains.

soil management The sum total of all tillage operations, cropping practices, fertilizer, lime, and other treatments conducted on or applied to a soil for the production of plants.

soil map A map showing the distribution of soil types or other soil mapping units in relation to the prominent physical and cultural features of the Earth's surface.

soil mechanics and engineering A subspecialization of soil science concerned with the effect of forces on the soil and the application of engineering principles to problems involving the soil.

soil moisture potential *See* soil water potential.

soil monolith A vertical section of a soil profile removed from the soil and mounted for display or study.

soil morphology The physical constitution, particularly the structural properties, of a soil profile as exhibited by the kinds, thicknesses, and arrangement of the horizons in the profile, and by the texture, structure, consistence, and porosity of each horizon.

soil order *See* order, soil.

soil organic matter The organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. Commonly determined as the amount of organic material contained in a soil sample passed through a 2-mm sieve.

Soil organic matter: The organic fraction of the soil that includes plant, animal and microbial residues in various stages of decomposition, biomass of soil microorganisms, and substances produced by plant roots and other soil organisms. It is commonly determined as the total organic (non-carbonate) carbon in a soil sample passed through a 2-mm sieve.

soil porosity *See* porosity, soil.

soil productivity *See* productivity, soil.

soil profile *See* profile, soil.

soil quality The capacity of a specific kind of soil to function physically, chemically and biologically, within natural or managed ecosystem boundaries, so as to maximize provisioning and regulatory ecosystem services. Often considered in relative to this capacity in the undisturbed, natural state.

soil reaction *See* reaction, soil; pH, soil.

soil salinity The amount of soluble salts in a soil, expressed in terms of percentage, milligrams per kilogram, parts per million (ppm), or other convenient ratios.

soil separates *See* separate, soil.

soil series *See* series, soil.

soil solution The aqueous liquid phase of the soil and its solutes, consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials.

soil strength A transient soil property related to the soil's solid phase cohesion and adhesion.

soil structure The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively.

soil structure classes A grouping of soil structural units or peds on the basis of size from the very fine to very coarse.

soil structure grades A grouping or classification of soil structure on the basis of inter- and intraaggregate adhesion, cohesion, or stability within the profile. Four grades of structure, designated from 0 to 3, are recognized: *structureless, weak*, *moderate*, and *strong*.

soil structure types A classification of soil structure based on the shape of the aggregates or peds and their arrangement in the profile,

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including platy, prismatic, columnar, blocky, subangular blocky, granulated, and crumb.

soil survey The systematic examination, description, classification, and mapping of soils in an area. Soil surveys are classified according to the kind and intensity of field examination.

soil temperature classes A criterion used to differentiate soil in *Soil Taxonomy*, mainly at the family level. Classes are based on mean annual soil temperature and on differences between summer and winter temperatures at a depth of 50 cm.

soil textural class A grouping of soil textural units based on the relative proportions of the various soil separates (sand, silt, and clay). These textural classes, listed from the coarsest to the finest in texture, are sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. There are several subclasses of the sand, loamy sand, and sandy loam classes based on the dominant particle size of the sand fraction (e.g., loamy fine sand, coarse sandy loam).

soil texture The relative proportions of the various soil separates in a soil.

soil water deficit The difference between PET and ET, representing the gap between the amount of evapotranspiration water atmospheric conditions "demand" and the amount the soil can actually supply. A measure of the limitation that water supply places on plant productivity.

soil water potential (total) A measure of the difference between the free energy state of soil water and that of pure water. Technically it is defined as "that amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermically an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water (at the point under consideration)." This *total* potential consists of *gravitational, matric*, and *osmotic* potentials.

solarization The process of heating a soil in the field by covering it with clear plastic sheeting during sunny conditions. The heat is meant to partially sterilize the upper 5 to 15 cm of soil to reduce pest and pathogen populations.

solum (pl. sola) The upper and most weathered part of the soil profile; the A, E, and B horizons.

sombric horizon A diagnostic subsurface horizon that contains illuvial humus but has a low cation exchange capacity and low percentage base saturation. Mostly restricted to cool, moist soils of high plateaus and mountainous areas of tropical and subtropical regions.

sorption The removal from the soil solution of an ion or molecule by adsorption and absorption. This term is often used when the exact mechanism of removal is not known.

species diversity The variety of different biological species present in an ecosystem. Generally, high diversity is marked by many species with few individuals in each.

species richness The number of different species present in an ecosystem, without regard to the distribution of individuals among those species.

specific gravity The ratio of the density of a mineral to the density of water at standard temperature and pressure.

specific heat capacity The amount of kinetic (heat) energy required to raise the temperature of 1 g of a substance (usually in reference to soil or soil components).

specific surface The solid particle surface area per unit mass or volume of the solid particles.

splash erosion The spattering of small soil particles caused by the impact of raindrops on very wet soils. The loosened and separated particles may or may not be subsequently removed by surface runoff.

spodic horizon A diagnostic subsurface horizon characterized by the illuvial accumulation of amorphous materials composed of aluminum and organic carbon with or without iron.

Spodosols An order in *Soil Taxonomy*. Soils with subsurface illuvial accumulations of organic matter and compounds of aluminum and usually iron. These soils are formed in acid, mainly coarse-textured materials in humid and mostly cool or temperate climates.

stem flow The process by which rain or irrigation water is directed by a plant canopy toward the plant stem so as to wet the soil unevenly under the plant canopy.

storm flow The folks or flow of water in a stream coming from surface runoff during or just after rainfall or snow melt. Opposite of *base flow*.

stratified Arranged in or composed of strata or layers.

strip-cropping The practice of growing crops that require different types of tillage, such as row and sod, in alternate strips along contours or across the prevailing direction of wind.

structure, soil *See* soil structure.

stubble mulch The stubble of crops or crop residues left essentially in place on the land as a surface cover before and during the preparation of the seedbed and at least partly during the growing of a succeeding crop.

subgroup, soil The *great groups* in *Soil Taxonomy* are subdivided into central concept subgroups that show the central properties of the great group, intergrade subgroups that show properties of more than one great group, and other subgroups for soils with atypical properties that are not characteristic of any great group.

submergence potential The positive hydrostatic pressure that occurs below the water table.

suborder, soil A category in *Soil Taxonomy* that narrows the ranges in soil moisture and temperature regimes, kinds of horizons, and composition, according to which of these is most important.

subsoil That part of the soil below the plow layer.

subsoiling Breaking of compact subsoils, without inverting them, with a special knife-like instrument (chisel), which is pulled through the soil at depths usually of 30 to 60 cm and at spacings usually of 1 to 2 m.

sulfidic Adjective used to describe sulfide-containing soil materials that initially have a pH > 4.0 and exhibit a drop of at least 0.5 pH unit within 8 weeks of aerated, moist incubation. Found in potential acid sulfate soils.

sulfuric horizon A diagnostic subsurface horizon in either mineral or organic soils that has a pH < 3.5 and fresh straw-colored mottles (called *jarosite mottles*). Forms by oxidation of sulfide-rich materials and is highly toxic to plants.

summer fallow *See* fallow.

surface runoff *See* runoff.

surface seal A thin layer of fine particles deposited on the surface of a soil that greatly reduces the permeability of the soil surface to water.

surface soil The uppermost part of the soil, ordinarily moved in tillage, or its equivalent in uncultivated soils. Ranges in depth from 7 to 25 cm. Frequently designated as the *plow layer*, the *Ap layer*, or the *Ap horizon*.

surface tension The elasticlike phenomenon resulting from the unbalanced attractions among liquid molecules (usually water) and between liquid and gaseous molecules (usually air) at the liquid–gas interface.

swamp An area of land that is usually wet or submerged under shallow fresh water and typically supports hydrophilic trees and shrubs.

symbiosis The living together in intimate association of two dissimilar organisms, the cohabitation being mutually beneficial.

synergism **(i)** The nonobligatory association between organisms that is mutually beneficial. Both populations can survive in their natural environment on their own, although, when formed, the association offers mutual advantages. **(ii)** The simultaneous actions of two or more factors that have a greater total effect together than the sum of their individual effects.

talus Fragments of rock and other soil material accumulated by gravity at the foot of cliffs or steep slopes.

taxonomy, soil The science of classification of soils; laws and principles governing the classifying of soil. Also a specific *soil*

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classification system developed by the U.S. Department of Agriculture.

tensiometer A device for measuring the negative pressure (or tension) of water in soil *in situ*; a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge.

tension, soil-moisture *See* soil water potential.

terrace (1) A level, usually narrow, plain bordering a river, lake, or the sea. Rivers sometimes are bordered by terraces at different levels. (2) A raised, more or less level or horizontal strip of earth usually constructed on or nearly on a contour and designed to make the land suitable for tillage and to prevent accelerated erosion by diverting water from undesirable channels of concentration; sometimes called *diversion terrace*.

tetrahedral sheet Sheet of horizontally linked, tetrahedron-shaped units that serve as one of the basic structural components of silicate (clay) minerals. Each unit consists of a central four-coordinated atom (e.g., Si, Al, Fe) surrounded by four oxygen atoms that, in turn, are linked with other nearby atoms (e.g., Si, Al, Fe), thereby serving as interunit linkages to hold the sheet together.

texture *See* soil texture.

thermal analysis (differential thermal analysis) A method of analyzing a soil sample for constituents, based on a differential rate of heating of the unknown and standard samples when a uniform source of heat is applied.

thermic A soil temperature class with mean annual temperature 15 to 22 °C.

thermophilic Pertaining to temperatures in the range of 45 to 90 °C, the range in which thermophilic organisms grow best and in which thermophilic composting takes place.

thermophilic organisms Organisms that grow readily at temperatures above 45 °C.

thixotrophy The property of certain clay soils of becoming fluid when jarred or agitated and then setting again when at rest. Similar to *quick*, as in quick clays or quicksand.

tile, drain Pipe made of burned clay, concrete, or ceramic material, in short lengths, usually laid with open joints to collect and carry excess water from the soil.

till (1) Unstratified glacial drift deposited directly by the ice and consisting of clay, sand, gravel, and boulders intermingled in any proportion. (2) To plow and prepare for seeding; to seed or cultivate the soil.

tillage The mechanical manipulation of soil for any purpose; but in agriculture it is usually restricted to the modifying of soil conditions for crop production.

tillage, conservation Any tillage sequence that reduces loss of soil or water relative to conventional tillage, which generally leaves at least 30% of the soil surface covered by residues, including the following systems:

- **minimum tillage** The minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions.
- **mulch tillage** Tillage or preparation of the soil in such a way that plant residues or other materials are left to cover the surface; also called *mulch farming, trash farming, stubble mulch tillage*, and *plowless farming*.
- **no-tillage system** A procedure whereby a crop is planted directly into a seedbed not tilled since harvest of the previous crop; also called *zero tillage*.
- **ridge till** Planting on ridges formed by cultivation during the previous growing period.
- **strip till** Planting is done in a narrow strip that has been tilled and mixed, leaving the remainder of the soil surface undisturbed.

tillage, conventional The combined primary and secondary tillage operations normally performed in preparing a seedbed for a given crop grown in a given geographic area. Usually said of non-conservation tillage.

tillage, primary Tillage that contributes to the major soil manipulation, commonly with a plow.

tillage, rotary An operation using a power-driven rotary tillage tool to loosen and mix soil.

tillage, secondary Any tillage operations following primary tillage designed to prepare a satisfactory seedbed for planting.

tilth The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

topdressing An application of fertilizer to a soil after the crop stand has been established.

toposequence A sequence of related soils that differ, one from the other, primarily because of *topography* as a soil-formation factor, with other factors constant.

topsoil (1) The layer of soil moved in cultivation. *See also* surface soil. (2) Presumably fertile soil material used to top-dress roadbanks, gardens, and lawns.

trace elements Elements present in the Earth's crust in concentrations less than 1000 mg/kg. When referring to plant nutrients, the term *micronutrients* is preferred.

trioctahedral An octahedral sheet of silicate clays in which the sites for the six-coordinated metallic atoms are mostly filled with divalent cations, such as Mg^{2+}.

trophic level Levels in a food chain that pass nutrients and energy from one group of organisms to another.

truncated Having lost all or part of the upper soil horizon or horizons.

tuff Volcanic ash usually more or less stratified and in various states of consolidation.

tundra A level or undulating treeless plain characteristic of arctic regions.

Ultisols An order in *Soil Taxonomy*. Soils that are low in bases and have subsurface horizons of illuvial clay accumulations. They are usually moist, but during the warm season of the year some are dry part of the time.

umbric epipedon A diagnostic surface horizon of mineral soil that has the same requirements as the mollic epipedon with respect to color, thickness, organic carbon content, consistence, structure, and P_2O_5 content, but that has a base saturation of less than 50%.

universal soil loss equation (USLE) An equation for predicting the average annual soil loss per unit area per year; $A = RKLSPC$, where R is the climatic erosivity factor (rainfall plus runoff), K is the soil erodibility factor, L is the length of slope, S is the percent slope, P is the soil erosion practice factor, and C is the cropping and management factor.

unsaturated flow The movement of water in a soil that is not filled to capacity with water.

vadose zone The aerated region of soil above the permanent water table.

value (color) *See* Munsell color system.

variable charge *See* pH-dependent charge.

varnish, desert A glossy sheen or coating on stones and gravel in arid regions.

vermicompost Compost made by earthworms eating raw organic materials in moist aerated piles, which are kept shallow to avoid heat buildup that could kill the worms.

vermiculite A 2:1-type silicate clay, usually formed from mica, that has a high net negative charge stemming mostly from extensive isomorphous substitution of aluminum for silicon in the tetrahedral sheet.

Vertisols An order in *Soil Taxonomy*. Clayey soils with high shrink–swell potential that have wide, deep cracks when dry. Most of these soils have distinct wet and dry periods throughout the year.

vesicles (1) Unconnected voids with smooth walls. (2) Spherical structures formed inside root cortical cells by vesicular arbuscular mycorrhizal fungi.

virgin soil A soil that has not been significantly disturbed from its natural condition.

water deficit (soil) The amount of available water removed from the soil within the vegetation's active rooting depth, or the amount of water required to bring the soil to field capacity.

water potential, soil *See* soil water potential.

water table The upper surface of groundwater or that level below which the soil is saturated with water.

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water table, perched The surface of a local zone of saturation held above the main body of groundwater by an impermeable layer of stratum, usually clay, and separated from the main body of groundwater by an unsaturated zone.

water use efficiency Dry matter or harvested portion of crop produced per unit of water consumed.

waterlogged Saturated with water.

watershed All the land and water within the geographical confines of a drainage divide or surrounding ridges that separate the area from neighboring watersheds.

water-stable aggregate A soil aggregate stable to the action of water, such as falling drops or agitation, as in wet-sieving analysis.

weathering All physical and chemical changes produced in rocks, at or near the Earth's surface, by atmospheric agents.

wetland An area of land that has hydric soil and hydrophytic vegetation, typically flooded for part of the year, and forming a transition zone between aquatic and terrestrial systems.

wetting front The boundary between the wetted soil and dry soil during infiltration of water.

wilting point (permanent wilting point) The moisture content of soil, on an oven-dry basis, at which plants wilt and fail to recover their turgidity when placed in a dark, humid atmosphere.

windbreak Planting of trees, shrubs, or other vegetation perpendicular, or nearly so, to the principal wind direction to protect soils, crops, homesteads, etc., from wind and snow.

xenobiotic Compounds foreign to biological systems. Often refers to compounds resistant to decomposition.

xerophytes Plants that grow in or on extremely dry soils or soil materials.

yield gap The difference between actual crop production levels at a given location with current management and the potential productivity of the soils and climate with best available management.

zero tillage *See* tillage, conservation.

zymogenous organisms So-called opportunist organisms found in soils in large numbers immediately following addition of readily decomposable organic materials. *Contrast with* autochthonous organisms. *See also* r-strategist.

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