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Chapter 3

Changing atmospheric carbon dioxide: A threat or benefit?

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Abstract

Atmospheric carbon dioxide (CO_2) concentrations are rapidly increasing, having risen by about 100 ppm over the last century. Atmospheric CO_2 is the basic photosynthetic building block of plants and is respired to generate the plant's energy. Atmospheric CO_2 in enhanced conditions is like an "all-you-can-eat buffet" for trees. But are there hidden threats from rising atmospheric CO_2? Are the world's forests sinks or sources of CO_2? What will they be in the future? Can we slow the rise in atmospheric CO_2 with more intensive forestry efforts? How effective can intensive forestry practices be in sequestering carbon? Simultaneous with increasing CO_2, other greenhouse gases such as NO_x and O_3 are also rapidly increasing in the atmosphere. Will these gases be beneficial or detrimental to trees under elevated CO_2? This chapter will address these questions and will use our current understanding of forest function to gain insight into how future forests will be affected by increasing greenhouse gases. Finally, we address the potential of afforestation, reforestation, agroforestry and forest management for increasing carbon sequestration.

1. Introduction

Atmospheric carbon dioxide (CO_2) currently limits the growth potential and growth rates of forest trees. However, it is rising at the rate of about $1\frac{1}{2}$–2% per

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year and is expected to double preindustrial-period concentrations in the 21st century (Keeling et al., 1995). Does this mean that the extra atmospheric CO_2 will be beneficial or detrimental to forest trees? For example, will the rapidly rising temperature associated with elevated atmospheric CO_2 and other greenhouse gases cause massive diebacks, declines and changes in species ranges? These questions will be addressed in this paper and we will examine the potential for large scale afforestation and reforestation efforts to slow the rise in atmospheric CO_2.

2. Growth responses

Thousands of studies have been conducted to examine the impacts of elevated atmospheric CO_2 on plant photosynthesis, growth, and physiology (see reviews by Bazzaz and Fajer, 1992; Ceulemans and Mousseau, 1994; Mooney and Koch, 1994; Lee and Jarvis, 1995; Curtis and Wang, 1998; Ceulemans et al., 1999; Medlyn et al., 1999; Norby et al., 1999; Luo et al., 1999; Körner, 2000; Karnosky et al., 2001; Medlyn et al., 2001). Yet, no consensus has been developed as to whether long-term forest productivity will increase, decrease, or remain the same under elevated CO_2. While photosynthetic enhancement averages 60% under elevated CO_2 and growth enhancement averages about 27% (Norby et al., 1999), most studies have been conducted for relatively short time periods and they have been conducted in artificial conditions where plants are not exposed to other stresses or to competition (Körner, 2000; Karnosky, 2003).

2.1. Long-term studies

Long-term (we define “long-term” as 3 years or longer) studies of forest tree growth under elevated CO_2 are highly variable (0–97% enhancement) in their results suggesting that species (Norby et al., 1992; Rey and Jarvis, 1997; Tissue et al., 1997; Jach et al., 2000; Pokorný et al., 2001; Ceulemans et al., 2002; Dijkstra et al., 2002; Percy et al., 2002), genotype (Isebrands et al., 2001), soil fertility (Johnson et al., 1998; Oren et al., 2001; Sigurdsson et al., 2001; Maroco et al., 2002), and competition (McDonald et al., 2002) can affect responses. Studies where growth enhancement was found generally attributed a substantial portion of this effect to increased leaf area under elevated CO_2 in young trees (Taylor et al., 2001; Maroco et al., 2002) and enhanced photosynthetic capacity (Tissue et al., 1997; Noormets et al., 2001). While a general long-term growth trend is to have a large initial increase in growth followed by little or no increase after that

(Centritto et al. 1999a, 1999b), some studies have reported continued increases in growth enhancement throughout their studies (Pokorný et al., 2001; Dijkstra et al., 2002; Percy et al., 2002).

Whether or not growth increases will continue in closed-canopy conditions where leaf area index is not likely to be affected by elevated CO_2 and where CO_2 enhancement of photosynthesis is limited by shade is still unknown. However, Norby et al. (2002) has provided the first evidence of sustained increase in forest productivity in a closed-canopy forest. Certainly, the long-term nature of forest ecosystem responses to elevated atmospheric CO_2 is still a critical research need and one that is complicated by the coupled nature of carbon and nitrogen cycles and how these feedback to forest growth and productivity through litter fall, litter decomposition, and biogeochemical processes such as mineralization and nitrification needs critical investigation (Woodward, 2002).

It is important to note that increased photosynthesis or growth is not equivalent to increased C sequestration. The size of the C pool is not necessarily correlated with growth but rather "residence time", or how long the accumulated C actually remains in the ecosystem. Because no studies have followed forest stand development from generation to maturity, there is no evidence that residence time increases with increased exposure to CO_2, and in fact the opposite may be true.

2.2. Co-occurring stresses

Trees and forests are being exposed simultaneously to increasing atmospheric CO_2 and other stresses such as air pollution, excess nitrogen deposition or nitrogen deficiency, drought, and increasing temperatures. How will these co-occurring stresses affect responses to elevated CO_2?

2.3. Nitrogen

Globally, forests are facing steadily increasing levels of nitrogen additions related to deposition from the burning of fossil fuels (Galloway, 1989; Norby, 1998). Since most forest soils are nitrogen poor, the initial response of forest trees to increasing nitrogen levels has generally been to accelerate growth (Lloyd, 1999; Schraml et al., 2002). Studies of elevated atmospheric CO_2 and increased nitrogen deposition have generally seen greater CO_2 enhancement under higher nitrogen levels (Kerstiens et al., 1995; Murray et al., 2000a). For forests near or at "nitrogen saturation", as are many of the European forests whose soils have been contaminated by excessive nitrogen deposition for the past 100 years, it is less likely that CO_2 enhancement will occur. To verify this hypothesis, there is a need to conduct elevated CO_2 studies in those forests to

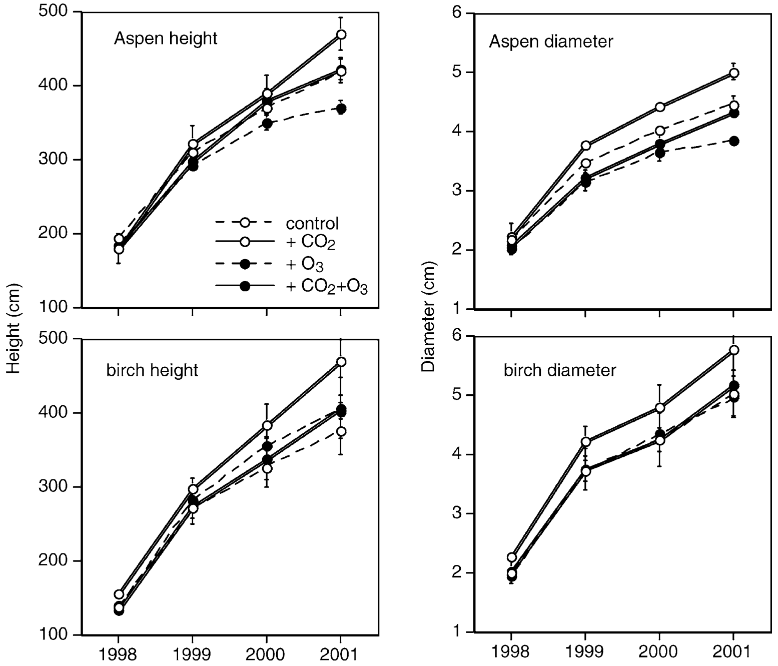

Figure 1. Impacts of interacting elevated atmospheric CO_2 and O_3 on height and diameter growth for trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*) (Aspen data from Percy et al., 2002).

more accurately predict forest ecosystem responses to co-occurring elevated CO_2 and high nitrogen.

2.4. Ozone

Tropospheric ozone (O_3) is increasing worldwide at about the same rate as CO_2 (Fowler et al., 1999; IPCC, 2001). Currently, about 25% of the world's forests are exposed to damaging levels of O_3 and nearly 50% of the world's forests are expected to be exposed to damaging O_3 levels by the year 2100 (Fowler et al., 1999). Since CO_2 generally enhances growth and O_3 usually suppresses growth, it is not surprising that co-occurring $CO_2 + O_3$ generally cancel out one another (Isebrands et al., 2001; Percy et al., 2002; McDonald et al., 2002). In the largest and longest running $CO_2 + O_3$ interaction study, the growth enhancement by elevated atmospheric CO_2 is completely lost when O_3 is present at concentrations already occurring over much of the eastern United States (Isebrands et al., 2001; Percy et al., 2002; McDonald et al., 2002; Fig. 1).

2.5. Drought

As the climate changes, it is likely that the frequency and severity of droughts will increase (Cubasch et al., 2001). Since water availability largely controls tree growth (Maurer et al., 1999), there is a considerable interest developing in investigating elevated CO_2/drought interactions (Wullschleger et al., 2002). Will growth enhancement by elevated CO_2 be negated under water-limiting environments? Or, will the decreased stomatal conductance and improved water use efficiency under elevated atmospheric CO_2 mean that growth stimulation in water-limited environments is greater than in water-rich environments?

Various elevated CO_2/drought interaction studies suggest that the interaction depends on severity and frequency of drought (Centritto et al. 1999a, 1999b), and tree species (Tschaplinski et al., 1995; Samuelson and Seiler, 1993; Catovsky and Bazzaz, 1999). Competitive interactions among species under elevated CO_2 can be strongly influenced by water availability (Groninger et al., 1995; Catovsky and Bazzaz, 1999) suggesting that forest community structure may be altered in water-limited environments for forests exposed to elevated CO_2.

2.6. High temperature events

As global warming continues, there will be more frequent occurrence of high temperature stress events (Mearns et al., 1984). Whether these will have more or less effect on forest tree growth under increasing CO_2 is not known. While both increasing temperature and CO_2 are predicted to increase light-saturated photosynthetic rates and apparent quantum yields (Lewis et al., 1999), the positive effect of warmer temperatures on the CO_2-induced stimulation of photosynthesis and growth is not always observed (Olszyk et al., 1998; Tjoelker et al. 1998a, 1998b; Bruhn et al., 2000; Kellomaki and Wang, 2001). Regarding high temperature stress in combination with elevated atmospheric CO_2, some studies have shown that elevated CO_2 decreases the adverse effects of high temperature (Kriedmann et al., 1976; Faria et al. 1996, 1999; Wayne et al., 1998). Others have found an increased susceptibility to heat stress when trees are grown under elevated CO_2 (Bassow et al., 1994). Clearly, this interaction is critically important for adaptation of tree species to the rapidly changing temperature regimes and needs further examination.

3. Global warming: effects on forest ecosystems

As CO_2 and other greenhouse gases (tropospheric O_3, methane, nitrogen oxides, etc.) are increasing in the atmosphere, they are trapping radiant energy,

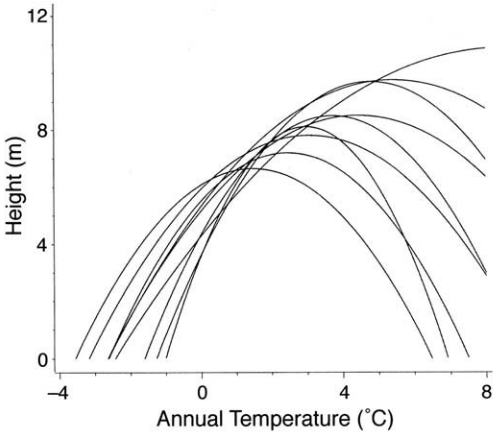

Figure 2. Response functions of mean annual temperature as a predictor of height for nine populations for *Pinus contorta latifolia* (from Rehfeldt et al., 1999).

causing global warming (IPCC, 2001; Houghton et al., 2001). In the past century, mean global surface temperatures have increased 0.6 °C (Houghton et al., 2001). The recent warming trend is indisputable (Mann et al., 1998) and the link to anthropogenic causes is clear (IPCC, 2001; Houghton et al., 2001). The global climate is predicted to become increasingly warmer through this century with mean temperatures expected to increase from 1–5 °C (Stott et al., 2000; Stott and Kettleborough, 2002).

3.1. Species richness and range

Rising temperatures and elevated atmospheric CO_2 both tend to increase forest growth and productivity (Hasenauer et al., 1999; Caspersen et al., 2001) as do the related changes in seasonal phenology that are linked to global warming (Menzel and Fabian, 1999; Peñuelas and Filella, 2001; Parmesan and Yohe, 2003). Paradoxically, these same changes will first likely increase forest productivity but in the long term may cause major forest dieback and decline resulting in species shifts, migrations and/or extinctions (Davis and Shaw, 2001; Rehfeldt et al. 1999, 2002). Trees are adapted to their environment and populations have optimal temperatures for growth (Rehfeldt et al., 1999; Fig. 2). This large genetic variability in response has allowed tree species to adapt to change. This variability, in combination with long-distance seed and pollen dispersal has facilitated previous migrations, during both glaciation and post glaciation periods (Davis and Shaw, 2001). Currently, however, the unparalleled rate of the current global warming, along

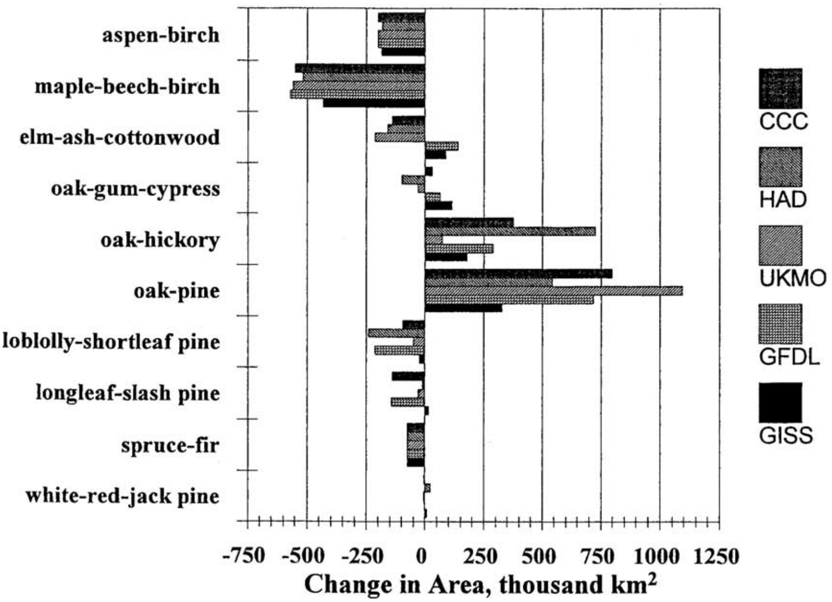

Figure 3. Potential change in area occupied by forest types in the Eastern US under five climate change scenarios (from: Iverson and Prasad, 2001). Note that the analysis has a firm boundary at the Canadian border; thus, the summary statistics do not include potentially compensating changes farther north.

with the widespread fragmentation of habitats due to anthropogenic disturbances has ecologists concerned that many species will not be able to adapt or migrate fast enough in the next century; thus, resulting in major changes in species richness and forest community types (Price et al., 1999; Currie, 2001; Iverson and Prasad, 2001; Fig. 3).

3.2. Soil

The response of root and microbial respiration to global warming is critically important in determining the response of vegetation to global climatic change (Atkin et al., 2000) and in determining if northern latitude forests will be sources or sinks of carbon (C) in the future (Rustad and Fernandez, 1998; Melillo et al., 2002). Thus, understanding how belowground systems respond to warming temperatures will be critical.

Soil warming will largely impact two main systems: the tree roots, particularly fine roots, and the microbial communities involved in litter decomposition. Root respiration is very sensitive to temperature as fine root turnover and root growth both increase with increasing temperature. Root respiration provides the energy and C skeletons necessary for ion uptake and the synthesis and maintenance of root biomass (Atkin et al., 2000). It is also a major source of CO_2 loss in plants, with 8–52% of the CO_2 fixed in photosynthesis being released back into the atmosphere by root respiration (Lambers et al., 1996). Increased soil respiration has been demonstrated to occur under elevated CO_2 (King et al., 2001a; Schlesinger and Lichter, 2001) and under elevated temperatures (Peterjohn et al., 1994; Atkin et al., 2000; Pregitzer et al., 2000). Increased frequency of hot days under global warming is likely to substantially increase soil respiration (Atkin et al., 2000).

Fine root production and turnover rates are likely tightly linked to the impact of new C from the canopy during the growing season (Pregitzer et al., 2000) so they are closely linked to whole-canopy assimilation. Both fine root growth and turnover have been shown to increase under elevated CO_2 (Tingey et al., 2000) and temperatures (King et al., 1999). However, no perceivable change in allocation of carbon to roots versus shoots has yet been detected (van Noordwijk et al., 1998).

In addition to plant respiration, litter decomposition plays a central role in regulating the balance between C assimilation and release to the atmosphere (Rustad and Fernandez, 1998). It is well known that litter decomposition is increased dramatically under increasing temperatures (Rustad and Fernandez, 1998; McHale et al., 1998; MacDonald et al., 1999; Melillo et al., 2002). However, it is less clear what effects elevated CO_2 have on litter decomposition (Norby et al., 2000). Predicted decreases under elevated CO_2 are largely predicated on changes in foliar chemical composition, which can be substantial (King et al., 2001b; Lindroth et al., 2001) or on altered microbial populations (Larson et al., 2002; Phillips et al., 2002) or their function (Zak et al. 2000a, 2000b).

3.3. Global warming and pests

Changes in atmospheric CO_2, other greenhouse gases, and related global warming, are likely to have major impacts on the occurrence, distribution, and abundance of both insect (Kopper et al., 2002; Percy et al., 2002; Kopper and Lindroth, 2003) and disease pests (Karnosky et al., 2002) that could have immense implications for the growth, productivity and biogeochemistry of future forests. The reader is referred to Chapter 1 for more information on this subject.

3.4. Net effects on carbon storage

These changes in species composition, soil biogeochemistry, and pests will surely have some effect on C storage in forest ecosystems. The net effect will

Table 1. Global carbon stocks in vegetation and the top mass of soils (from FAO, 2001)

		Global C Stocks (Gt C)		
Biome	Area (10^6 km^2)	Vegetation	Soils	Total
Tropical forests	17.6	212	216	428
Temperature forests	10.4	59	100	159
Boreal forests	13.7	88	471	559
Tropical savannas	22.5	66	264	330
Temperate grasslands	12.5	9	295	304
Deserts/semideserts	45.5	8	191	199
Tundra	9.5	6	121	127
Wetlands	3.5	15	225	240
Croplands	16.0	3	128	131
Total	151.2	466	2011	2477

depend on factors such as the degree and timing of warming, changes in precipitation and moisture availability, threshold responses, ecosystem resilience, and interactions with co-occurring stresses (Scheffer et al., 2001). Model simulations have generated hypotheses about future change in carbon storage. An emerging hypothesis from multiple models is that the early effect of a modest temperature increase is higher ecosystem productivity and carbon storage, but without a corresponding precipitation increase, ecosystems could rapidly shift to drought-induced dieback and release of carbon back to the atmosphere (Aber et al., 2001). It should be noted here that decomposition, not productivity, regulates C storage. For example, boreal forests have historically had relatively high C storage even though they have low productivity because they have low decomposition rates. In contrast, C storage in the tropical soils is limited even though productivity is high as decomposition is very high. Thus, temperature and moisture drive decomposition rates.

4. Afforestation and reforestation for carbon sequestration

Forest vegetation represents a major pool in the global cycle (Schroeder et al., 1997). Forest vegetation alone contains 350–460 Gt C (Dixon et al., 1994; FAO, 2001). Forest soils store another 2000 Gt C (FAO, 2001, Table 1). The exact size of these C pools remains an active research question as does the effect of elevated greenhouse gases and the associated global warming on these pools (Ciais et al., 1995; Fan et al., 1998; Field and Fung, 1999; Fung, 2000; Kaiser, 2000; Field, 2001; Pacala et al., 2001; Brown, 2002). We know that harvesting has a major impact on C storage of individual forest tracts (Pypker

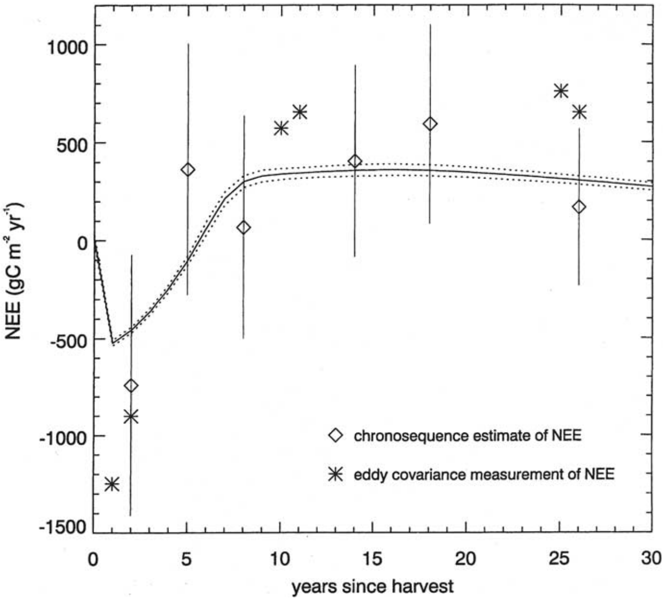

Figure 4. The effects of harvesting on C budgets is shown here in this modeled mean (solid line) and interannual standard deviation (dotted line) for simulated net ecosystem carbon exchange following harvest in a slash pine plantation at a Florida site. Eddy flux measurements of 10 EE from actual harvest site data are also shown (from Thornton et al., 2002).

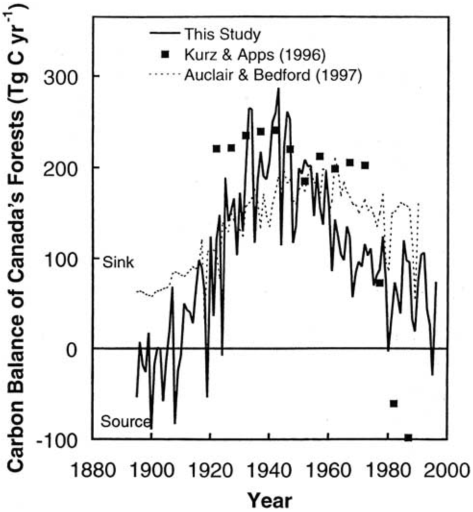

Figure 5. Comparison of C balance of Canada's forests as estimated by Chen et al. (2000) (this study), Kurz and Apps (1996) and Auclair and Bedford (1997) (from Chen et al., 2000).

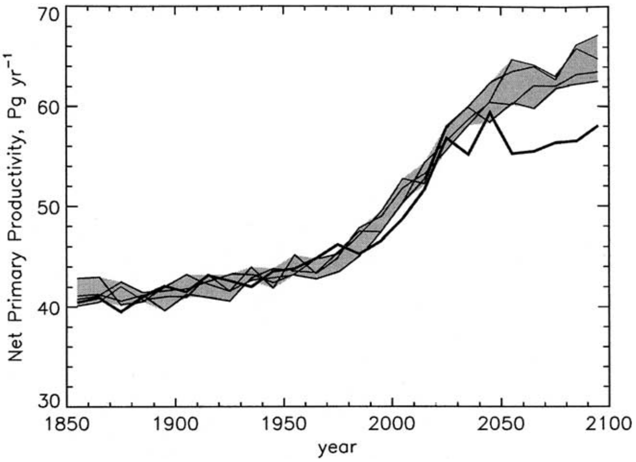

Figure 6. Global annual net primary productivity predicted by various dynamic global vegetation models (from White et al., 1999).

and Fredeen, 2002; Thornton et al., 2002; Fig. 4) and that larger forest regions are highly dynamic in their carbon balance (Kurz and Apps, 1999; Chen et al., 2000; Fig. 5) and particularly sensitive to disturbances such as insects, diseases and fire (Kurz and Apps, 1999; Goodale et al., 2002).

It is a demanding challenge to predict how forests will change in C sink or source strength under a rapidly changing climate and in the face of anthropogenic disturbances (Schroeder et al., 1997; Caspersen et al., 2001). Generally, forest productivity is predicted to increase under the changing climate for the next 50 years before stabilizing. Increases in photorespiration and maintenance respiration may cause a leveling off of photosynthesis stimulation and increasing soil respiration may limit productivity (White et al., 1999; Cox et al., 2000; Fig. 6). However, it should be noted that the C sink strength of forests is highly variable depending on forest types, forest age, moisture availability, local climate, and soil carrying capacity (Lloyd, 1999; Fig. 7).

Clearly, better-managed and fully-stocked forests and forests established with genetically superior selections offer considerable opportunities for increasing the C sink strength of the world's forests. For example, currently over 80% of the estimated C sink in northern hemisphere forests occurs in one-third of the forest (Goodale et al., 2002). It has been estimated that another 757–1144 Mt C/yr could be sequestered in the world's forests by afforestation, reforestation, improved forest management, and increased agroforestry (Kaiser, 2000; Table 2). This increased C sequestration potential under more intensive forestry practices is being closely examined as a method to decrease the buildup of CO_2 in the atmosphere (Schroeder, 1991;

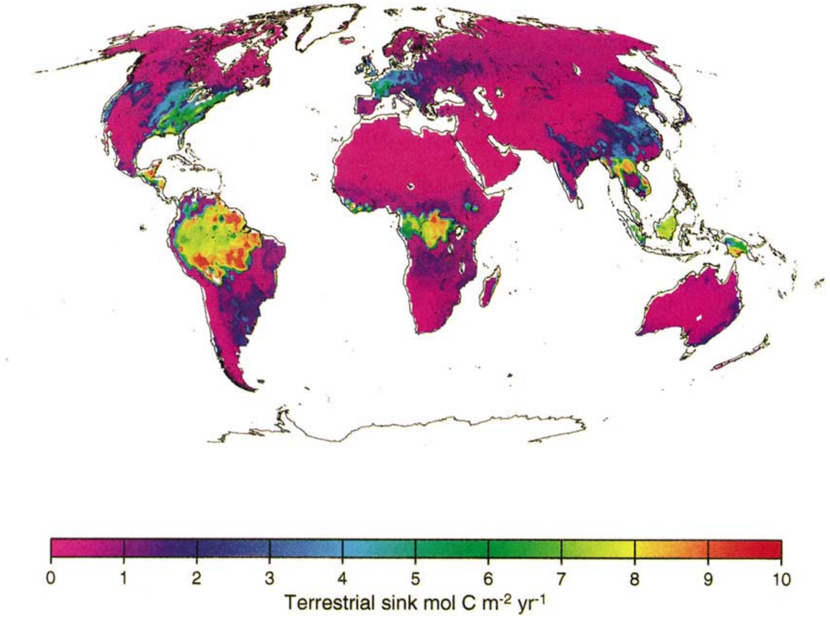

Figure 7. The modeled global terrestrial CO_2 sink (from Lloyd, 1999).

Nilsson and Schopfhauser, 1995; Boman and Turnbull, 1997; Winjum and Schroeder, 1997; Fig. 8).

4.1. Traditional forests

Increasing forest productivity via intensive forestry offers considerable possibilities to sequester C including:

- using more productive trees,
- using more intensive forest management,
- increasing the acreage in afforestation and reforestation,
- substituting wood for other materials (such as plastic or metal), and
- substituting wood for other fuels (i.e., coal or oil) (Nilsson and Schopfhauser, 1995; Marland and Schlamadinger, 1997; Winjum et al., 1998; Johnsen et al., 2001; Liski et al., 2001; Table 3).

All forest biomes have undergone major changes in distribution since the last ice age (18 000 years ago) (FAO, 2001). The resulting forests now occupying these lands are not necessarily the optimal trees for forest productivity. Simply changing the species composition in a reforestation program can have a large

Table 2. Effects of various activities on carbon storage (from Kaiser, 2000)

	Carbon (10^{-6} tonn C yr^{-1})
Deforestation	up to 1788
Newly planted and regrowing forests	197 to 584
Better management of:	
• croplands	125
• grazing lands	240
• forests	170
Changes in land use	
• agroforestry	390
• cropland to grassland	38
Other	42

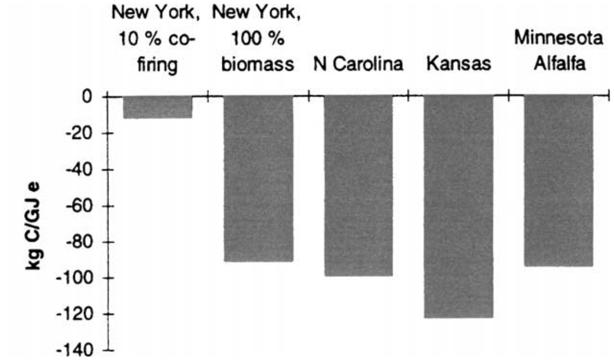

Figure 8. Reduced carbon dioxide emissions compared with a cool-based system (Kg C GJ^{-1} of electricity) (from Boman and Turnbull, 1997).

impact on “C” sequestration potential as can be seen for a comparison of three northern conifers in northern Michigan (Fig. 9).

The C sequestration potential of various afforestation/reforestation activities also depends on the site and forest management practices and forest type. Typical sequestration rates are 0.8–2.4 tons of C per year in boreal forests, 0.7–7.5 tons in temperate forests, and 3.2–10 tons in the tropical forests (Brown et al., 1996). Expansion of the world’s plantations (Table 4) could increase C sequestration by some 38 Gt through the year 2050 (Brown et al., 1996; Tables 5 and 6).

Carbon sequestration policy

Under the Kyoto Protocol (Murray et al., 2000b) national emissions or uptake of C by forests are accounted on an annual basis and expressed

Table 3. There are a number of ways in which forestry research can improve the capacity of forest trees to sequester carbon

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Near Term

Genetics

- Species changes on an existing site (optimizing species)
- Selection of the best seed sources, hybrids, or clones available today

Management

- Fertilization
- Weed control
- Irrigation
- Pest control
- Planting density

Future

Genetics and Biotechnology

- Clones selected for future climate (higher temperature, higher CO_2, etc.)
- Improve stress tolerance through genetic engineering (Metting et al., 2001)
- Genetic engineering of altered carbon allocation to stems and roots (Metting et al., 2001)
- Genetic engineering of decreased height growth, optimized photoperiod response, altered branching patterns, pest resistance or improved world chemistry (Tuskan, personal communication)
- Genetic engineering of decreased volatile organic compound production (Tuskan, personal communication)
- Genetic engineering of compounds to decrease rates of decomposition

Soils

- Selecting and/or engineering mycorrhizae to optimize tree growth rates
- Engineering “carbon-holding” soils

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as tons of CO_2 released or sequestered (FAO, 2001). While underdeveloped countries can get C credits for decreasing forest destruction, the 39 developed countries (“Annex I”) can achieve part of their greenhouse gas emission targets by enhancing sinks through CO_2 absorption in terrestrial ecosystems through land-use change and forestry (Murray et al., 2000b; Schulze et al., 2002). Thus, the Kyoto Protocol and other national policies have generated worldwide interest in forestry practices that will result in increasing C sequestration (Cannell, 1999; Sohngen and Sedjo, 2000; Lindner, 2000; Harmon, 2001; Scholes and Noble, 2001; Fang et al., 2001). Furthermore, they have generated a rudimentary “carbon market” that is developing in financial and technological transfers to support forestry projects that sequester C or protect C stocks (Smith et al., 2000; McCarl and Schneider, 2001; Plantinga and Mauldin, 2001). Some countries have already initiated massive

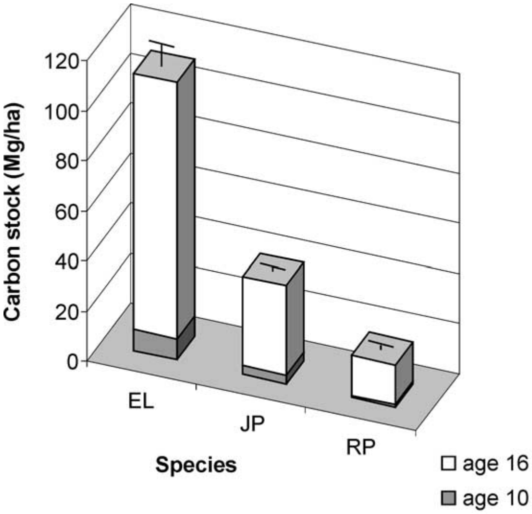

Figure 9. Comparison of the relative carbon storage potential at ages 10 and 16 of three northern temperate conifers (E.L. = European larch [*Larix decidua* Mill.], JP = jack pine [*Pinus banksiana* Lamb.], and RP = red pine [*Pinus resinosa* Ait.]) (from Kinouchi et al., 2003).

Table 4. The world's forests (from FAO, 2001)

Region	Forest (10^6 ha)	% of all forests	Natural forest (10^6 ha)	Forest plantations
Africa	650	17	642	8
Asia	548	14	432	116
Europe	1039	27	1007	32
North America	549	14	532	18
Oceania	198	5	194	3
South America	886	23	875	10
	3869	100	3682	187

tree planting programs including Canada (van Kooten et al., 1999) and China (Fang et al., 2001). For example, in a program aimed at sequestering C, restoring deforested landscapes, and stopping desertification, China has committed $12.7 billion to planting hundreds of millions of trees over the next decade (Xu et al., 2001).

4.2. Urban forests

Urban forests cover large and expanding areas of developed and developing countries around the world and offer considerable opportunities for in-

Table 5. Potential contribution of afforestation/reforestation and agroforestry activities to global carbon sequestration, 1995–2050 (from Brown et al., 1996)

Activity	Gt
Tropical afforestation/reforestation	16.7
Temperate afforestation/reforestation	11.8
Tropical agroforestry	6.5
Boreal afforestation/reforestation	2.3
Temperate agroforestry	0.7
	38.0

Table 6. Rotation periods and corresponding mean annual increments (MAIs) (from Nilsson and Schopfhauser, 1995)

Region/species	Rotation period (yr)	MAI (m^3 ha^{-1} yr^{-1})
New Zealand/coniferous	25	25
Australia/coniferous	30	25
Australia/deciduous	30	22
South Africa/coniferous	25	16
Tropical Africa/deciduous	30	17
Tropical Africa/coniferous	30	15
Tropical Latin America/coniferous	15	18
Tropical Latin American/deciduous	20	25
Temperate Latin America/coniferous + deciduous	30	22
Tropical Asia/coniferous + deciduous	20	16
US south/coniferous	35	15
US temperate/coniferous	50	10
Europe:		
Nordic countries	60	5
EC-9	40	8
Central	60	6
Southern	20	10
Eastern	60	6
Former Soviet Union	80	3
Canada	60	4
China	80	2.3
Temperate Asia	40	12.0

creasing C sequestration with tree planting. Approximately 3.5% of the US is currently classified as urban with the area in metropolitan areas having increased threefold between 1950 and 1990 (Dwyer et al., 2003). It has been estimated that urban trees currently store 700 million tons of C, with an annual sequestration rate of 22.8 million tons (Nowak and Crane, 2002, Ta-

Table 7. Estimated carbon storage, gross and net annual sequestration, number of trees, and percent tree cover for ten US cities (from Nowak and Crane, 2002)

City	Storage (t C)	Annual sequestration		No. Trees ($\times 10^3$)
		Gross (t C/yr)	Net (t C/yr)	
New York, NY	1 225 200	38 400	20 800	5 212
Atlanta, GA	1 220 200	42 100	32 200	9 415
Sacramento, CA	1 107 300	20 200	na	1 733
Chicago, IL	854 800	40 100	na	4 128
Baltimore, MD	528 700	14 800	10 800	2 835
Philadelphia, PA	481 000	14 600	10 700	2 113
Boston, MA	289 800	9 500	6 900	1 183
Syracuse, NY	148 300	4 700	3 500	891
Oakland, CA	145 800	na	na	1 588
Jersey City, NJ	19 300	800	600	136

ble 7). In addition, the air-conditioning and space-heating savings reduce a significant number of CO_2 emissions (as much as 0.29 t/ha) (Heisler, 1974; McPherson, 1998).

Tree planting remains a viable option for most urban areas around the world as mortality has generally far outnumbered replanting in most cities over the past century (Gerhold et al., 2001). Planting can be done along streets, median strips, parking lots, parks, gardens, cemeteries, and in some little thought of places such as rooftops and under power lines with utility-compatible trees (Karnosky and Karnosky, 1985; Johnson and Gerhold, 2001; Fig. 10). In addition to sequestering C, urban trees help ameliorate the microclimate, provide wildlife habitat, increase property values, impact human moods, absorb air pollutants, conserve water, reduce soil erosion, and decrease noise pollution (Karnosky, 1984; Berrang and Karnosky, 1983).

With the rapid rate of urbanization that is occurring worldwide, there is clearly a need for expanded research into the role of urban forests and urban tree planting in C sequestration. The little research to date shows considerable potential for increasing C sequestration in urban forests.

4.3. Can forests be long-term carbon sinks?

Because of widespread interest in using forest C sequestration to supplement emissions reduction as a strategy to reduce atmospheric CO_2, the question of sink permanence is often raised. As the previous discussion has clearly shown, there is uncertainty about maintaining C storage in ecosystems affected by multiple stresses. But uncertainty about forest growth and health is not new. Even in the absence of climate change forests have some risk of damage and loss of C from disturbances such as harvesting, insects, diseases, and weather.

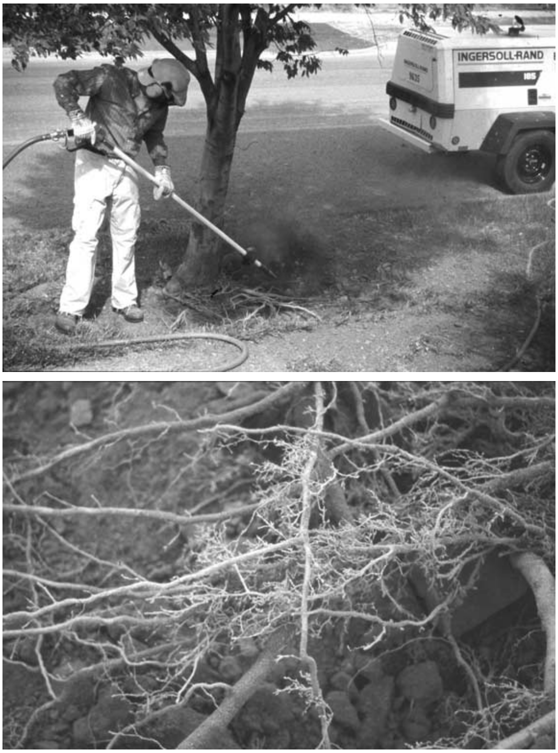

Figure 10. Urban trees have the potential to sequester carbon (see Table 7). Here, an urban tree in State College, Pennsylvania, is being excavated to examine total carbon storage of this street tree (photos by Henry Gerhold) (from Johnson, 2002).

In the 1980s, forests in the Northeastern US lost approximately 44.6 million tons/yr of C due to harvesting (some remains sequestered in solid wood products and landfills), and 11.2 million tons/yr of C due to mortality from all causes (some remains sequestered in coarse woody debris) (Birdsey, 1992). Together these annual losses comprised 2.3 percent of the live biomass. Despite atmospheric changes such as increased CO_2 and ozone concentrations, and significant amounts of sulfur and nitrogen deposition, Northeastern forests remain healthy overall and have sustained sufficient growth to allow significant accumulation of C. An important factor in maintaining healthy forests is the combined federal, state, and landowner effort to protect forests from fire, insects and diseases.

Historical data from the Northeastern US show that afforestation can successfully sequester C for more than 100 years. Large areas of forests in the Northeastern US are regrowing on agricultural land that was abandoned in the

1800s. According to recent forest inventory data, northeastern forests are currently accumulating C in live biomass at a rate of about 1 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Birdsey and Heath, 1995). Johnson and Strimbeck (1995) measured the change in biomass and soil C over a 33-year period for 23 stands of aggrading sugar maple in Vermont, ranging in age (at initial measurement in 1957–1959) from 47 to 97 years, and found that only 2 stands lost biomass while 21 gained biomass. The average gain in biomass for all stands was 1.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. There was no detectable change in soil C over this period.

Some news reports have concluded that because field experiments now show that the effects of increasing atmospheric CO_2 are less than previously thought, the potential use of forests as C sinks is less feasible (e.g., Ferber, 2001). However, most analyses that attempt to determine the potential of forests for enhancing C sequestration do not include the effects of increased CO_2 in the estimates to begin with (e.g., Brown et al., 1996). The effectiveness of C sequestration strategies will depend on the continued management and protection of forest resource productivity and health provided by the nation's land managers.

5. Conclusions and knowledge gaps

The process of photosynthesis, which results in assimilation of C into plants, is currently limited by CO_2 availability in most tree species. Thus, increasing atmospheric CO_2 generally increases photosynthesis and growth in the short-term for trees growing individually or in small numbers in chambers. Less certain is how forest trees will respond in forest stands, under competition, and exposed to other stresses as well as co-occurring greenhouse gases such as O_3 which have a tendency to diminish or completely eliminate growth enhancement under elevated CO_2. Thus, long-term growth and productivity studies under realistic forest conditions and with co-occurring natural stresses are needed to reduce the uncertainty in this issue.

The world's forests vary dramatically in terms of being C sources or sinks such that the largest sinks are highly productive tropical forests. Also, strong sinks are the temperate forests of North America, Europe and Asia. Boreal forests are weak sinks, or in some cases sources, but they may contain large soil C pools. Global warming will likely affect the sink strength of all the world's forests but especially vulnerable to change are the temperate and boreal forests which may undergo large-scale changes in species richness and range. The rates of change are yet largely uncertain and use of genetically diverse planting stock will slow the rate of change and increase the adaptability of regeneration stock.

Intensive forestry efforts, including afforestation, reforestation, agroforestry, and improved forest management intensity offer opportunities to slow the rise in atmospheric CO_2. These efforts can also be used to displace a significant amount of fossil fuels further slowing the rise of atmospheric CO_2. In addition, these “C forestry” practices can have many positive environmental impacts, especially when practiced on degraded lands. Although climate change and interactions with multiple stresses are likely to increase the risk of losing C storage in forests, there is yet no evidence that the current impact of climate change and other stresses on C storage has been significant. Using C sequestration to slow the rise in atmospheric CO_2 is very likely to remain a viable part of a comprehensive strategy to manage greenhouse gases for at least the next several decades. Certainly, this remains a very important forest research topic as no one has studied “C” budgets of forest stands from establishment through harvest.

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