CHAPTER 3

PRINCIPLES OF ENERGY BEHAVIOUR APPLIED TO ENVIRONMENTAL ISSUES

3.1. FUNDAMENTAL CONCEPTS RELATED TO ENERGY.

Energy is defined as the ability to do work, and the behaviour of energy can be described by the first and second laws of thermodynamics.

P.3.1. The first law of thermodynamics states that energy may be transformed from one type to another but is never created or destroyed.

It can also be applied in a more ecological way as follows: you can not get something for nothing - there is no such thing as a free lunch (Commoner, 1971).

Thus when a change of any kind occurs in a closed system (see 2.3 for definition) an increase or decrease in the internal energy occurs, heat is evolved or absorbed and work is done. Therefore:

$$\Delta E = Q + W \tag{3.1}$$

where

ΔE = change in internal energy

Q = heat absorbed

W = work done on the system

As mentioned in 2.1 a relationship exists between mass and energy, which dictates that energy is produced as a result of nuclear processes. Equation (3.1) assumes that such processes have not taken place.

In environmental science we are primarily concerned with the quantity of incident solar energy per unit area in an ecosystem and the efficiency with which this energy is converted by organisms into other forms. This situation is illustrated in Fig. 3.1, where the fate of solar radiation upon grass-herb vegetation of an old field community in Michigan is shown (Golley, 1960).

The transformation of solar energy to chemical energy by plants conforms with the first law of thermodynamics:

$$\text{Solar energy assimilated by plants} = \text{chemical energy of plant tissue} + \text{heat energy of respiration} \quad (3.2)$$

For the next level in the foodchain, the herbivorous animals, the energy balance can also be set up:

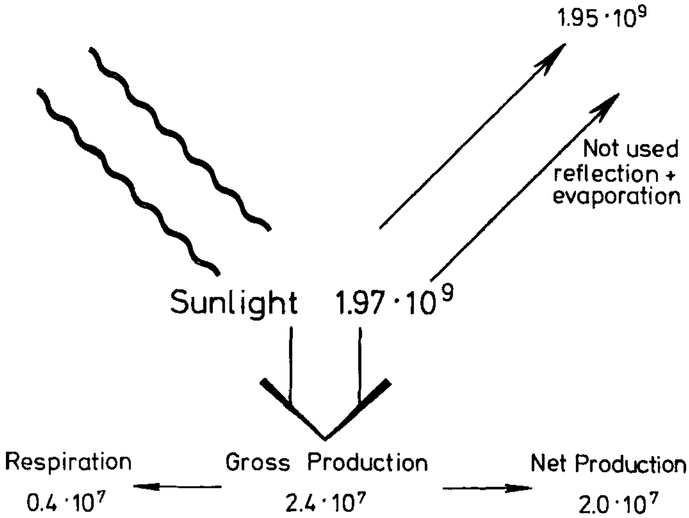

Fig. 3.1. Fate of solar energy incident upon the perennial grass-herb vegetation of an old field community in Michigan. All values in J m^{-2} y^{-1}.

$$F = A + UD = G + H + UD \quad (3.3)$$

where
F = the food intake converted to energy (Joule)
A = the energy assimilated by the animals
UD = undigested food or the chemical energy of faeces
G = chemical energy of animal growth
H = the heat energy of respiration

These considerations pursue the same lines as those mentioned in 2.8, where the mass conservation principle was applied. The conversion of biomass to chemical energy is illustrated in Table 3.1.

P.3.2. In nature we can distinguish two processes: spontaneous processes which occur naturally without an input of energy from outside and non-spontaneous processes, which require an input of energy from outside. These facts are included in the second law of thermodynamics, which states that processes involving energy transformations will not occur spontaneously unless there is a degradation of energy from a non-random to a random form, or from a concentrated into a dispersed form. In other words all energy transformations will involve energy of high quality being degraded to energy of lower quality (e.g. potential energy to heat energy). The quality of energy is measured by means of the thermodynamic state variable entropy (high quality ~ low entropy).

TABLE 3.1
A. Heat combustion of animal material

Oragnism	Species	Heat of combustion (kcal/ash-free gm)
Ciliate	Tetrahymena pyriformis	-5.938
Hydra	Hydra littoralis	-6.034
Green hydra	Chlorohydra viridissima	-5.729
Flatworm	Dugesia tigrina	-6.286
Terrestrial flatworm	Bipalium kewense	-5.684
Aquatic snail	Succinea ovalis	-5.415
Brachiipod	Gottidia pyramidata	-4.397
Brinc shrimp	Artemia sp.(nauplii)	-6.737
Cladocera	Leptodora kindtii	-5.605
Copepod	Calanus helgolandicus	-5.400
Copepod	Trigriopus californicus	-5.515
Caddis fly	Pycnopsyche lepido	-5.687
Caddis fly	Pycnopsyche guttifer	-5.706
Spit bug	Philenus leucopthalmus	-6.962
Mite	Tyroglyphus lintneri	-5.808
Bettle	Tenebrio molitor	-6.314
Guppie	Lebistes reticulatus	-5.823

TABLE 3.1 (continued)
B. Energy values in an Andropogon virginicus Old-Field Community in Georgia

Component	Energy value (kcal/ash-free gm)
Green grass	-4.373
Standing dead vegetation	-4.290
Litter	-4.139
Roots	-4.167
Green herbs	-4.288
Average	-4.251

C. Heat combustion of migratory and nonmigratory birds

Sample	Ash-free material (kcal/gm)	Fat ratio (% dry weight as fat)
Fall birds	-8.08	71.7
Spring birds	-7.04	44.1
Nonmigrants	-6.26	21.2
Extracted bird fat	-9.03	100.0
Fat extracted: fall birds	-5.47	0.0
Fat extracted: spring birds	-5.41	0.0
Fat extracted: nonmigrants	-5.44	0.0

D. Heat of combustion of components of biomass

Material	ΔH protein (kcal/gm)	ΔH fat (kcal/gm)	ΔH carbohydrate (kcal/gm)
Eggs	-5.75	-9.50	-3.75
Gelatin	-5.27	-9.50	
Glycogen			-4.19
Meat, fish	-5.65	-9.50	
Milk	-5.65	-9.25	-3.95
Fruits	-5.20	-9.30	-4.00
Grain	-5.80	-9.30	-4.20
Sucrose			-3.95
Glucose			-3.75
Mushroom	-5.00	-9.30	-4.10
Yeast	-5.00	-9.30	-4.20

Source Morowitz, 1969

The second law of thermodynamics can be more precisely expressed as the existence of a state variable S, defined by:

$$dS = d_e S + d_i S \tag{3.4}$$

where $d_e S = dQ/T$ and $d_i S \geq 0$ (= 0 for reversible processes), which will change during any process such that dS (universe ≥ 0).

Organisms, ecosystems and the entire ecosphere possess the essential thermodynamic characteristic of being able to create and maintain a high state of internal order or a condition of low entropy (entropy can be said to measure disorder, lack of information on molecular details, or the amount of unavailable energy). Low entropy is achieved by a continual dissipation of energy of high utility - light or food - to energy of low utility - heat. Order is maintained in the ecosystem by respiration, which continually produces disorder (heat).

P.3.3. The second law of thermodynamics explains why ecosystems can maintain organization or order. A system tends spontaneously toward increasing disorder (or randomness), and if we consider the system to consist of an ecosystem and its surroundings, we can understand that order (negative entropy) can be produced in the ecosystem if more disorder (entropy) is produced in its surroundings. In the ecosystem the ratio of total community respiration to the total community biomass (denoted as the R/B ratio) can be regarded as the maintenance to structure ratio or as a thermodynamic order function for homogeneous systems.

The behaviour of energy in an ecosystem can conveniently be termed the energy flow, because the energy transformation occurs only in one direction towards lower quality energy. However, as the chemical compounds carry chemical energy and the elements cycle (see 2.5), energy will also cycle. Solar radiation is the inflowing energy, which is used by phototrophic organisms to produce biomass. The chemical energy in the biological matter produced is of a non-random character, but at the same time heat is produced by respiration and becomes the outflowing energy. The chemical cycling of the elements is a result of this unidirectional flow of energy. Without solar radiation there would be no order in the ecosystem and no cycling of elements would take place.

P.3.4. From a physical standpoint the environmental crisis is an entropy crisis, as pollution makes disorder.

An example of this is given in Fig. 2.45, which illustrates the accumulation of lead in the Greenland ice pack from 800 B.C. to the present. This steadily increased accumulation demonstrates that lead released to the atmosphere is distributed worldwide and that entropy is correspondingly increased. That entropy is increased by distribution of pollutants, can be demonstrated by a simple model consisting of two bulbs of equal volume, connected with a stop cock. If one chamber contains one mole of a pure gas and the second is empty, then opening the valve between the two chambres causes an increase in entropy of:

$$\Delta_e S \equiv \int \frac{dQ}{T} = \frac{Q}{T} = -W = R * \ln \frac{V_2}{V_1} = R * \ln 2 \qquad (3.5)$$

where $\Delta_e S$ = the increase in entropy, V_2 = the volume occupied by the mole of gas after the valve was opened, while V_1 is the volume before the valve was opened.

Thus paradoxically, the more we attempt to maintain order, the more energy we require and the greater stress we inevitably put on the environment.

3.2. ENERGY USE AND ENERGY RESOURCES.

A human needs about 9,000 kJ per day to survive, but today the average inhabitant in the most developed countries uses more than 900,000 kJ, 100 times more than the survival level. Most energy is consumed by the industrial nations. They have 30% of the world's population but consume 80% of the world's energy.

Paragraph 2.8 has shown that only 10-20% of the initial biomass can be used by the organisms on the next level in the foodchain. As biomass can be translated into energy (see Table 3.1), this is also true of energy transformation through a foodchain. This implies that the short foodchain of grain — human should be prefered to the longer and more wasteful grain — animal — human.

Of course the problem of food shortage cannot be solved so simply, since animals produce proteins with a more favourable amino acid composition for human food (lysine is missing in plant proteins) and eat plants that cannot all be used as human food at present. But to a certain extent food production can be increased by making the foodchain as short as possible.

This concept also applies to the use of fossil fuel or other energy sources. Fig. 3.2 shows such an energy chain where the more links there are the greater the waste of energy.

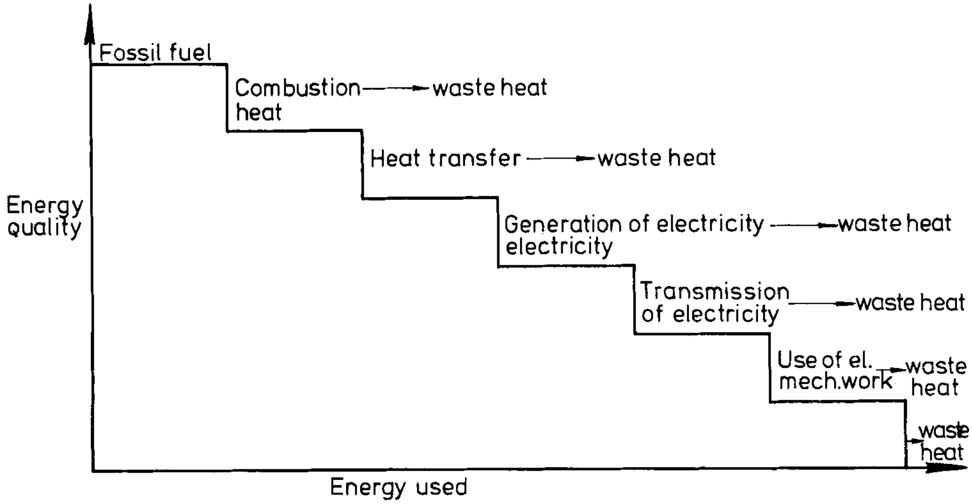

Fig. 3.2. Degradation of energy through an energy chain.

P.3.5. At each link in the chain energy is transferred from one form to another and heat is wasted as a consequence of the second law of thermodynamics.

In Table 3.2 is listed the net energy efficiency for some of the most commonly used energy systems. We cannot escape the second law of thermodynamics, but we can minimize energy waste:

1. by keeping the energy chain *as short as possible,*
2. *by increasing the efficiency,* i.e. the ratio of useful energy output to the total energy input,
3. *by wasting as little heat to the surroundings as possible,* e.g. by *insulation,* and *using heat produced by energy transfer* heat produced at power stations can be used for heating purposes).

The first law of thermodynamics can also be applied to the energy situation. The only free energy available is solar radiation, because the earth is an open system that gets energy from external sources; if we have to get energy from other sources it will always cost energy to provide energy. For example, at present only one third of the oil in an average reservoir is recovered, and the energy needed to produce the steam that is rejected into the borehole to increase the recovery may exceeds the energy recovered as oil. As a result, although total energy production is declining total energy consumption is increasing.

TABLE 3.2
The energy efficiencies of common individual systems

Conversion system	Percentage efficiency approximately
Processing of natural gas	97
Mining of nuclear fuel (uranium)	95
Processing of coal	92
Processing of oil	88
Home natural gas furnace	85
Electric car storage battery	80
Surface mining of coal	78
Extraction of natural gas	73
Propeller driven wind turbine	70
Home oil furnace	65
Fuel cell	60
Processing of nuclear fuel	57
Deep mining of coal	55
Fossil fuel power plant with proposed MHD topping cycle	50
Steam turbine engine	45
Diesel engine	42
Offshore oil well	40
Fossil fuel power plant and proposed nuclear breeder plant	38
Today's nuclear power plant	31
Internal combustion engine	30
Fluorescent lamp	28
Wankel engine	22
Advanced solar cells (if developed)	15
Today's solar cells	10
Incandescent lamp	5

Fig. 3.3 demonstrates how steeply energy consumption has been in this century, and that the gap in per capita energy consumption between developed and developing nations is widening.

Based on the best possible information available today, it seems clear that the major supplies of oil and gas will probably run out somewhere between the years 2025 and 2050, while there is still sufficient coal for 200-400 years. Coal, however, cannot replace oil and gas completely because of pollution problems (see 2.6 and 3.5). Since it takes 25 to 50 years to develop a new energy system we have no time to loose in seeking replacements for oil and gas.

We will not go further into energy problems, since this book is concerned with the principles of environmental science, but it is worth mentioning that the world's greatest energy problem today is food: about 40% of the world's population do not receive the basic minimum quantity or quality of energy needed to maintain good health.

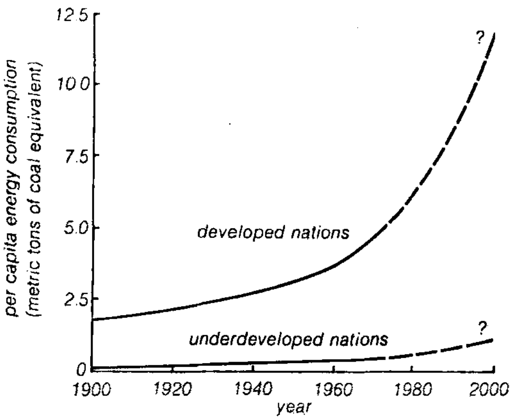

Fig. 3.3. The gap in per capita energy consumption between the developed nations and the underdeveloped nations is widening. (Source: United Nations)

3.3. PRODUCTIVITY.

The *primary productivity* of an ecological system is defined as the rate at which radiant energy is stored by the photosynthetic and chemosynthetic activity of producer organisms, chiefly green plants, as chemical energy in the form of organic matter. As unit is often used g (kcal, kJ) or g dry matter per m^2 og m^3 per 24h or per year. It is essential to distinguish between *gross primary productivity,* which is the total rate of synthesis including the organic matter used up in *respiration*, and *net primary productivity,* which is the rate of storage of organic matter. The rate of energy storage at consumer levels is referred to as *secondary productivity*.

The standing crop of biomass present at any given time must not be confused with net productivity, which is the change in biomass per unit of time:

$$P = \frac{dB}{dt} = f(B, \text{temp, environmental factors}) \qquad (3.6)$$

where P = productivity, B = biomass.

Table 3.3 gives some characteristic figures for gross and net primary productivity and Table 3.4 gives the estimated annual gross primary production of the biosphere and its distribution among major ecosystems.

TABLE 3.3
Characteristic figures for gross and net primary producion

Ecosystem	Gross prim. production	Net prim. production
Agricultural land	650 g dry weight $m^{-2}y^{-1}$ (range 100-4000)	
Alfalfa field	24000 kcal $m^{-2}y^{-1}$	15200 kcal $m^{-2}y^{-1}$
Desert	200 kcal $m^{-2}y^{-1}$	150 kcal $m^{-2}y^{-1}$
Oak-Pine forest	11500 kcal $m^{-2}y^{-1}$	5000 kcal $m^{-2}y^{-1}$
Pine forest	12200 kcal $m^{-2}y^{-1}$	7500 kcal $m^{-2}y^{-1}$
Rain forest	45000 kcal $m^{-2}y^{-1}$	13000 kcal $m^{-2}y^{-1}$
Coal reef	18.2 g dry weight $m^{-2}day^{-1}$	
Grassland	1200 g dry weight $m^{-2}y^{-1}$ (range 250-2500)	500 g dry weight $m^{-2}y^{-1}$ (range 150-1500)
Eutrophic lakes	2.1 g dry weight $m^{-2}day^{-1}$	
Sargasso Sea	0.5 g dry weight $m^{-2}day^{-1}$	
Silver Spring	17.5-35 g dry weight $m^{-2}day^{-1}$	
Total biosphere	2000 kcal $m^{-2}y^{-1}$	
Temperate forest	8000 kcal $m^{-2}y^{-1}$	3600 kcal $m^{-2}y^{-1}$

TABLE 3.4
Estimated gross primary production (annual basis) of the biosphere and its distribution among major ecosystems

Ecosystem	Area (10^6 km^2)	Gross Primary Productivity ($kcal/m^2/year$)	Total Gross Production (10^{16} kcal/year)
Marine *)			
Open ocean	326.0	1,000	32.6
Coastal zones	34.0	3,000	6.8
Upwelling zones	0.4	6,000	0.2
Estuaries and reefs	2.0	20,000	4.0
Subtotal	362.4	-	43.6
Terrestrial **)			
Deserts and tundras	40.0	200	0.8
Grasslands and pastures	42.0	2,500	10.5
Dry forests	9.4	2,500	2.4
Boreal coniferous forests	10.0	3,000	3.0
Cultivated lands with little or no energy subsidy	10.0	3,000	3.0
Moist temperate forest	4.9	8,000	3.9
Fuel subsidized (mechanized agriculture	4.0	12,000	4.8
Wet tropical and subtropical (broadleaved evergreen forests)	14.7	20,000	29.0
Subtotal	135.0	-	57.4
Total for biosphere (not included ice caps) (round figures)	500.0	2,000	100.0

*) Marine productivity estimated by multiplying Ryther's (1969) net carbon production figures by 10 to get kcal, then doublin these figures to estimate gross production and adding an estimate for estuaries (not included in his calculations).

**) Terrestrial productivity based on Lieth's (1963) net production figure doubled for low biomass systems and tripled for high biomass systems (which have high respiration) as estimates of gross productivity. Tropical forests have been upgraded in light of recent studies, and the industrialized (fuel subsidized) agriculture of Europe, North America, and Japan have been separated from the subsistence agriculture characteristic of most of the world's cultivated lands.

TABLE 3.5 A
Annual yields of edible food and estimated net primary production of major food crops at three levels: (1) Fuel subsidized agriculture (U.S.A., Canada, Europe or Japan); (2) Little or no fuel subsidy (India, Brazil, Indonesia or Cuba); (3) World average

	Edible portions		Estimated net primary production	
	Harvest weight *) (kg/ha)	Caloric content **) (kcal/m^2)	Dry matter production §) (kcal/m^2)	Rate growing season o) (kcal/m^2/day)
Wheat				
Netherland	4,400	1,450	4,400	24.4
India	900	300	900	5.0
World average	1,300	430	1,300	7.2
Corn				
USA	4,300	1,510	4,500	25.0
India	1,000	350	1,100	6.1
World average	2,300	810	2,400	13.3
Rice				
Japan	5,100	1,840	5,500	30.6
Brazil	1,600	580	1,700	9.4
World average	2,100	760	2,300	12.8
White potatoes				
USA	22,700	2,040	4,100	22.8
India	7,700	700	1,400	7.8
World average	12,100	1,090	2,200	12.2
Sweet potatoes and yams				
Japan	20,000	1,800	3,600	20.0
Indonesia	6,300	570	1,100	6.1
World average	8,300	750	1,500	8.3
Soybeans				
Canada	2,000	800	2,400	13.3
Indonesia	640	260	780	4.3
World average	1,200	480	1,400	7.8
Sugar				
Hawaii (cane)	11,000	4,070	12,200	67.8
Netherlands (beets)	6,600	2,440	7,300	40.6
Cuba (cane)	3,300	1,220	3,700	20.6
World average (all sugar: beets and cane)	3,300	1,220	-	-

*) Mean value 1962-1966 compiled from "Production Yearbook" vol. 21 (1966), Food and Agricultural Organization, United Nations.
**) Conversion, kcal/gm harvested weight as follows: Wheat 3.3; Corn 3.5; Rice 3.6; Soybeans 4.0; Potatoes 0.9; Crude sugar 3.7 (see USDA Agriculture Handbook No. 8, 1963).
§) Estimated on basis of 3X edible portion for grains, soybeans and sugar, 2X for potatoes.
o) Estimated to be six months (180 days) except sugar cane where sugar yields are calculated on 12 months growing season (365 days).

TABLE 3.5 B
Net primary production and edible portion at 3 levels: 1) Developed countries (fuel-subsidized agriculture), 2) Developing countries (little or no fuel subsidy), 3) World average

	kJ m^{-2} Net primary production			kJ m^{-2} Edible portion		
	1	2	3	1	2	3
Wheat	18,000	3800	5400	6000	1300	1900
Corn	18,500	4500	10,000	6500	1600	3500
Rice	22,600	7000	9600	7500	2500	3500
White potatoes	17,000	5700	9000	8800	2850	4380
Sweet potatoes	15,000	4500	6400	7000	2500	3500
Soybeans	10,600	3300	6300	3500	1100	2000
Sugar	52,000	15,000	28,000	16,500	5000	9000

Primary production in terms of food is summarized in Table 3.5 A+B, where the major food crops in developed and developing countries are compared. As can be seen, the developing countries have a lower per area unit producion compared with the developed countries, which use fuel-subsidized agriculture.

In 1975 there were an estimated $4*10^9$ people in the world each requiring $4.2*10^6$ kJoules per year, amounting to a total of $17*10^{15}$ kJoules per year, which represents only about 0,5% of the net primary production of the biosphere.

However, we must add to this the huge food consumption of all domestic animals. The standing crops of livestock in the world are at least 5 times that of humans in terms of equivalent food requirements. Thus man and his domestic animals consume at least 6.5% of net production of the whole biosphere or at least 12.5% of that produced on land. In addition, man also consumes huge quantities of primary production in the form of fibers, so his percentage consumption of net production on land is actually 15%. But what if the population doubles? Will there be enough food? Can we still continue to use and eat animals? The situation is rapidly becoming critical, and our planning for the future, must include the following points:

1. No more than about 25% of the land is truly arable. Irrigation of huge areas of dry land will require large expenditure of money (energy) and will have some severe ecological side-effects.
2. We are able to reduce the number of domestic animals, but man's need for animal proteins must not be underestimated.
3. Theoretically crop yields in the developing countries can be increased significantly, but these countries do not have the money to invest in agriculture and have growing populations. Even now it is almost impossible to maintain the same per capita production of food, which is already

too small.

4. High productivity can only be maintained by the use of energy subsidies and will be accompanied byn environmental pollution due to the heavy use of machinery, herbicides, insecticides and fertilizers.

These points illustrate well how the environmental crisis, the energy crisis and the food crisis are linked together. Only the solution of all three problems simultaneously, can be considered a real solution.

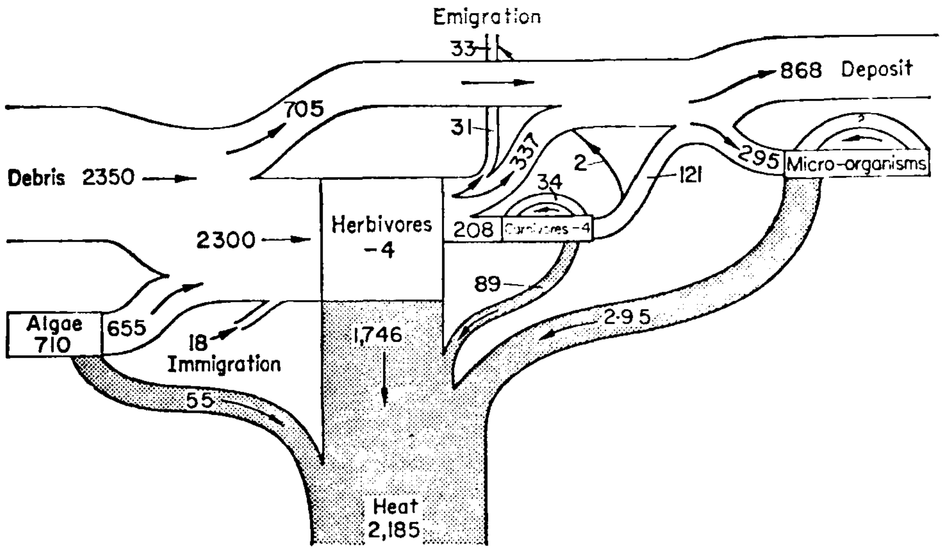

Fig. 3.4. Energy flow diagram for Root Spring, Concord, Mass., in 1953-54. Figures in kcal/m^2/year, numbers inside boxes indicate changes in standing crops. (From Teal, 1957)

3.4. ENERGY IN ECOSYSTEMS.

The transfer of energy from its source in the plants through herbivorous animals (primary consumers) to carnivorous animals (secondary consumers) and further to the top carnivore (tertiary consumers) is called *the foodchain.* By using the first law of thermodynamics an energy diagram can be set up, as illustrated in Figs. 3.4 and 3.5. The components for such a model of ecological energy flow are shown in Fig. 3.6.

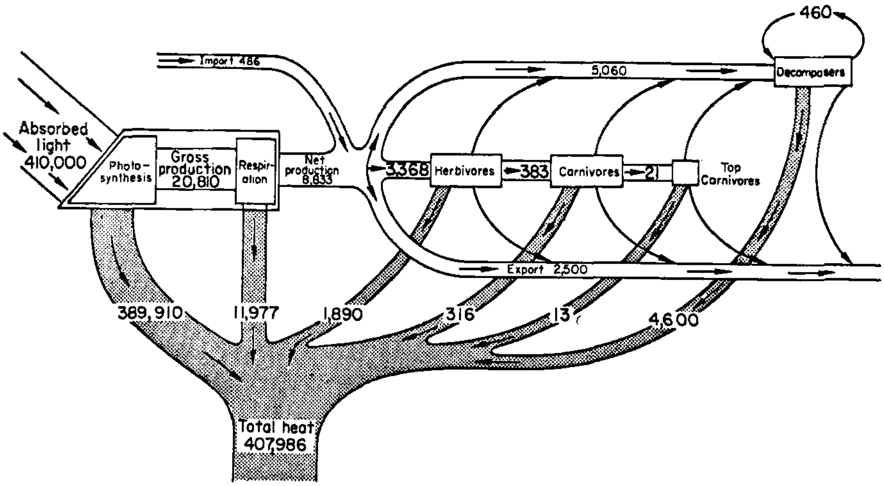

Fig. 3.5. Energy flow diagram for Silver Springs, Florida. Figures in kcal/m^2/year. (Adapted from Odum, 1957)

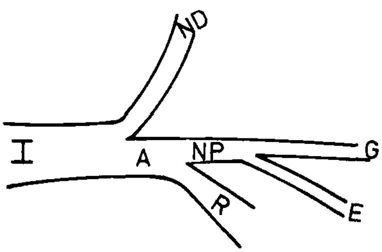

Fig. 3.6. Components for an ecological energy flow model. I = input of indigested food, ND = "nondigested" food or energy, A = assimilated energy, R = respiration, P = net production, E = excretion, G = growth (and reproduction). I = ND + A, A = NP + R, NP = G + E. Only G is available for next level in the foodchain at equilibrium.

In nature the food relationships are rarely as simple as a foodchain, but rather form a foodweb.

The relationships can also be illustrated by means of so-called ecological pyramids, which can either represent the number of individuals, the biomass (or energy content) or the energy flow on each level in the foodchain or foodweb (see Fig. 3.7). Only the energy flow forms a true pyramid, in accordance with the first law of thermodynamics. The number pyramids are affected by variation in size and the biomass pyramids by the metabolic rates of individuals.

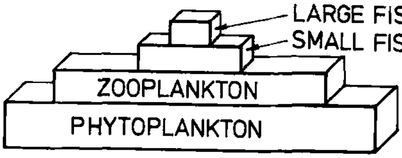

Fig. 3.7. An energy flow pyramid in the sea.

P.3.6. Ecological energy flows are of considerable environmental interest as calculation of biological magnifications are based on energy flows (see also 2.8).

This concept is illustrated in Table 2.24 taken from Woodwell et al. (1967).

Ecological efficiency should also be mentioned here, see Table 3.6, where some useful definitions are listed. Some characteristic efficiencies are listed in Tables 3.7 - 3.9.

TABLE 3.6
Ecological efficiency

Concept	Definition *)
Lindeman's efficiency	Ratio of energy intake level n to n-1: I_n/I_{n-1}
Trophic level assimilation efficiency	A_n/A_{n-1}
Trophic level production efficiency	NP_n/NP_{n-1}
Tissue growth efficiency	NP_n/A_n
Ecological growth efficiency	NP_n/I_n
Assimilation efficiency	A_n/I_n
Utilization efficiency	I_n/NP_{n-1}

*) For key to symbols used, see Fig 3.6

TABLE 3.7
Assimilation efficiency (A/I) for selected organisms
(after various authors)

Taxa	A/I value
Internal parasites	
Entomophagous Hymenoptera *Ichneumon* sp.	0.90
Carnivores	
Amphibian (*Nectophrynoides occidentalis*)	0.83
Lizard (*Mabuya buettneri*)	0.80
Praying mantis	0.80
Spiders	0.80 to 0.90
Warm- and cold-blooded herbivores	
Deer (*Odocoileus* sp.)	0.80
Vole (*Microtus* sp.)	0.70
Foraging termite (*Trinervitermes* sp.)	0.70
Impala antelope	0.60
Domestic cattle	0.44
Elephant (*Loxodonta*)	0.30
Pulmonate mollusc (*Cepaea* sp.)	0.33
Tropical cricket (*Orthochtha brachycnemis*)	0.20
Detritus eaters	
Termite (*Macrotermes* sp.)	0.30
Wood louse (*Philoscia muscorum*)	0.19
Soil-eating organisms	
Tropical earthworm (*Millsonia anomala*)	0.07

TABLE 3.8
Tissue Growth Efficiency (NP/A) for selected organisms
(after various authors)

Taxa	NP/A value	
Immobile, cold-blooded internal parasites		
Ichneumon sp.	0.65	
Cold-blooded, herbivorous and detritus-eating organisms		
Tropical cricket (*Orthochtha brachycnemis*)	0.42	
Other crickets	0.16	
Pulmonate mollusc (*Cepaea* sp.)	0.35	
Termite (*Macrotermes* sp.)	0.30	(?)
Termite (*Trinervitermes* sp.)	0.20	
Wood louse (*Philoscia muscorum*)	0.16	
Cold-blooded, carnivorous vertebrates and invertebrates		
Amphibian (*Nectophrynoides occidentalis*)	0.21	
Lizard (*Mabuya buettneri*)	0.14	
Spiders	0.40	
Warm-blooded birds and mammals		
Domestic cattle	0.057	
Impala antelope	0.039	
Vole (*Microtus* sp.)	0.028	
Elephant (*Loxodonta*)	0.015	
Deer (*Odocoileus* sp.)	0.014	
Savanna sparrow (*Passerculus* sp.)	0.011	
Shrews	Even lower values	

TABLE 3.9
Ecological Growth Efficiency (NP/I) for selected organisms
(after various authors)

Taxa	NP/I value
Herbivoruous mammals	
Domestic cattle	0.026 (0.44 x 0.057)
Impala antelope	0.022 (0.59 x 0.039)
Vole (*Microtus* sp.)	0.020 (0.70 x 0.285)
Deer (*Odocoileus* sp.)	0.012 (0.80 x 0.014)
Elephant (*Loxodonta*)	0.005 (0.30 x 0.015)
Birds	
Savanna sparrow (*Passerculus* sp.)	0.010 (0.90 x 0.011)
Herbivorous invertebrates	
Termite (*Trinervitermes* sp.)	0.140 (0.70 x 0.20)
Tropical cricket (*Orthochtha brachycnemis*)	0.085 (0.20 x 0.42)
Other crickets (New Zealand taxa)	0.050 (0.31 x 0.16)
Pulmonate mollusc (*Cepaea* sp.)	0.130 (0.33 x 0.30)
Detritus-eating and soil-eating invertebrates	
Termite (*Macrotermes* sp.)	0.090 (0.30 x 0.30)
Wood lause (*Philoscia muscorum*)	0.030 (0.19 x 0.16)
Tropical earthworm (*Millsonia anomala*)	0.005 (0.076 x 0.06)
Carnivorous vertebrates	
Lizard (*Mabuya* sp.)	0.100 (0.80 x 0.14)
Amphibian (*Nectophrynoides occidentalis*)	0.180 (0.83 x 0.21)
Carnivorous invertebrate	
Spiders	0.350 (0.85 x 0.42)
Internal parasites	
Ichneumon sp.	0.580 (0.90 x 0.65)

TABLE 3.10
Density, biomass, and energy flow of five primary consumer populations differing in size of individuals comprising the population

	Approximate density (m^2)	Biomass (g/m^2)	Energy flow ($kcal/m^2/day$)
Soil bacteria	10^{12}	0.001	1.0
Marine copepods (Acartia)	10^5	2.0	2.5
Intertidal snails (Littorina)	200	10.0	1.0
Salt marsh grasshoppers (Orchelimum)	10	1.0	0.4
Meadow mice (Microtus)	10^{-2}	0.6	0.7
Deer (Odicoileus)	10^{-5}	1.1	0.5

After E.P. Odum, 1968

P.3.7. There is a close relationship between energy flow rates and organism size.

Some of the most useful of these relationships are illustrated in Figs. 3.8-3.11 and in Table 3.10.

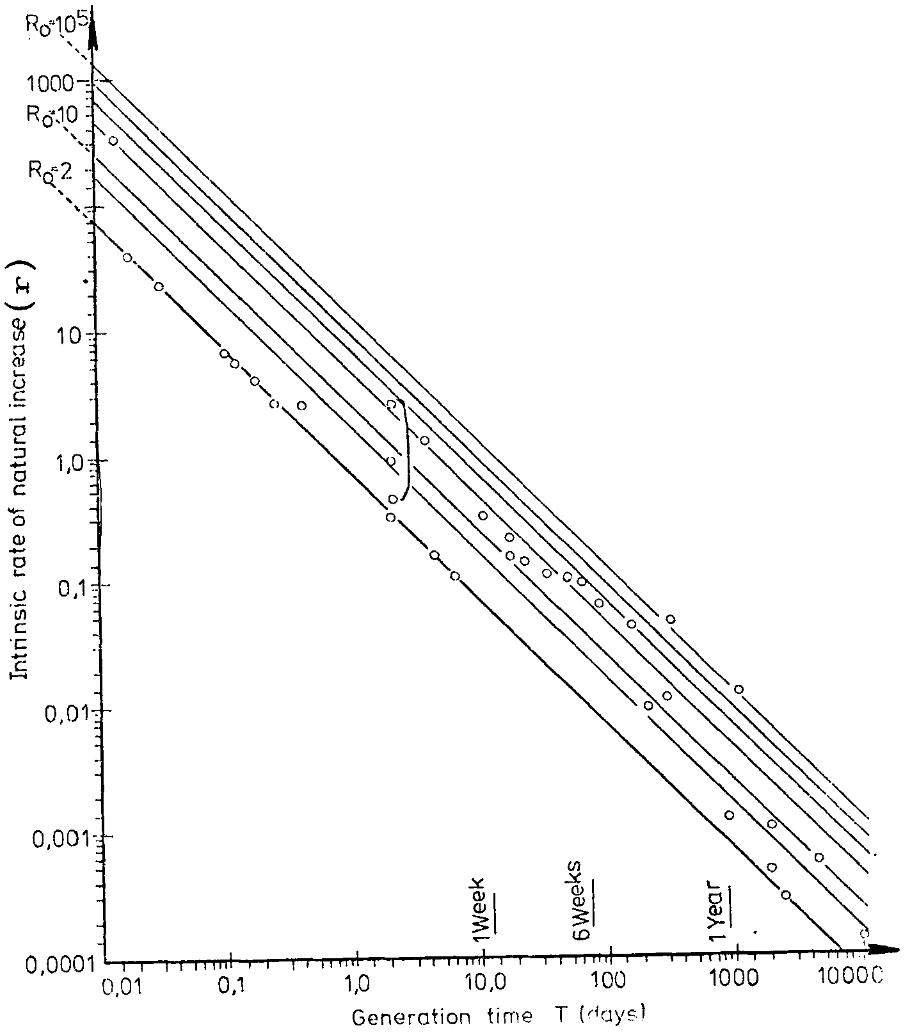

Fig 3.8. Intrinsic rate of natural increase plotted to generation time with diagonal lines representing net reproduction rate from 2 to 10^5 for a variety of organisms. (For definition of r, see 4.2)

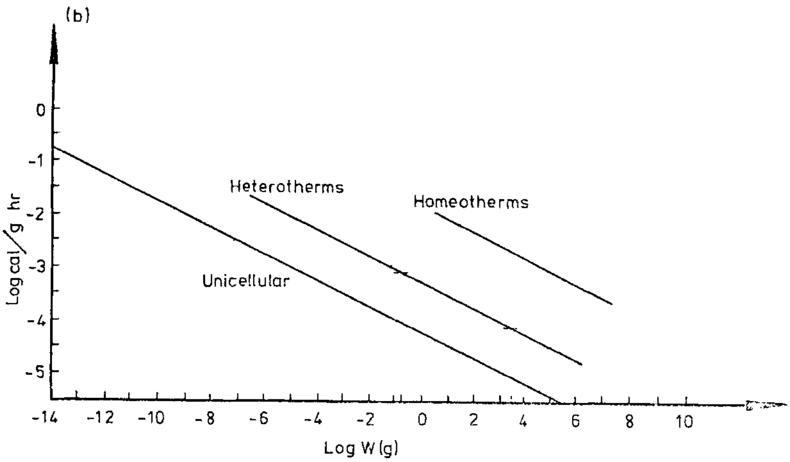

Fig. 3.9. The relationship of metabolic rate to weight for various animals.

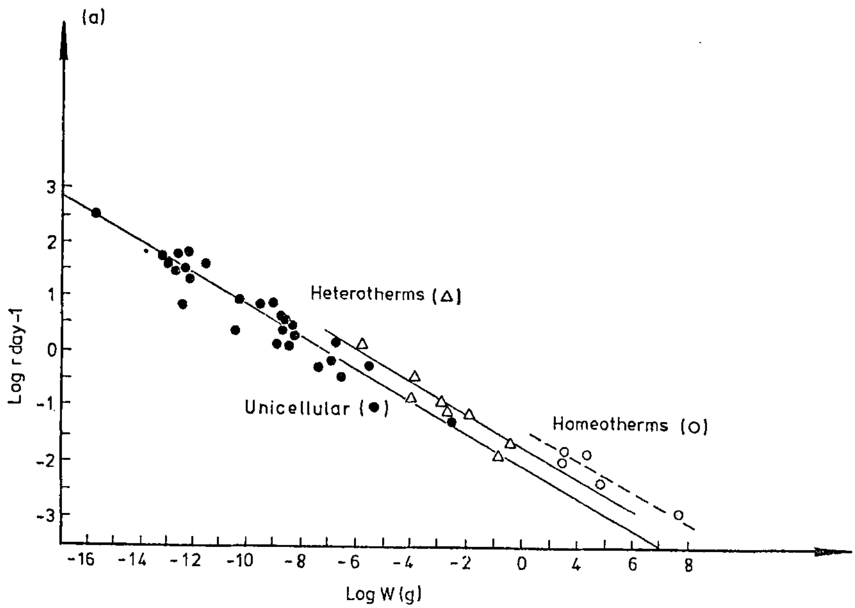

Fig. 3.10. Intrinsic rate of natural increase, r, to weight for various animals (for definition of r, see 4.2)

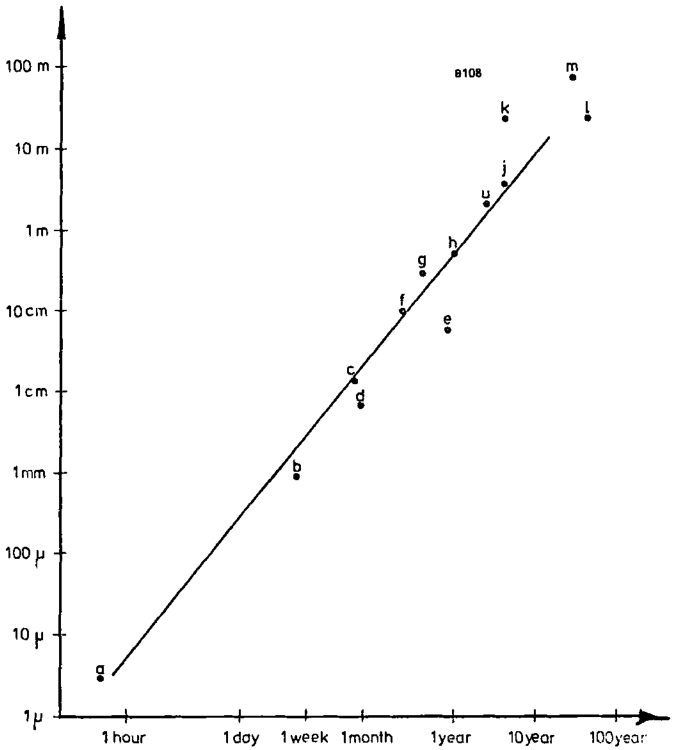

Fig. 3.11. Length and generation time plotted on log-log scale.

All these examples illustrate the fundamental relationship between size (surface) and the biochemical activity in the organisms. The surface determines the contact with the environment quantitatively, and thereby the possibility to take up food and excrete waste substances.

The same relationship explains the graphs shown in Figs. 3.12-3.15, where biochemical processes of toxic substances are involved.

These figures are constructed from literature data and, as seen, the excretion and uptake rates (for aquatic organisms) follow the same trends as the metabolic rate (Fig 3.9). This is of course not surprising, as the excretion is strongly dependent on the metabolism and the direct uptake is dependent on the surface.

The concentration factor, which indicates the ratio: concentration in the organism to the concentration in the medium, also follows the same lines, see Fig. 3.14. By equilibrium, the concentration factor can be expressed as the ratio between the uptake and excretion rates, as shown in Jørgensen (1979). As most concentration factors are determined by equilibrium, the relationship found in Fig. 3.14 seems reasonable. Intervals for concentration factors are here indicated for some species, in accordance with the literature (see Jørgensen et al., 1980).

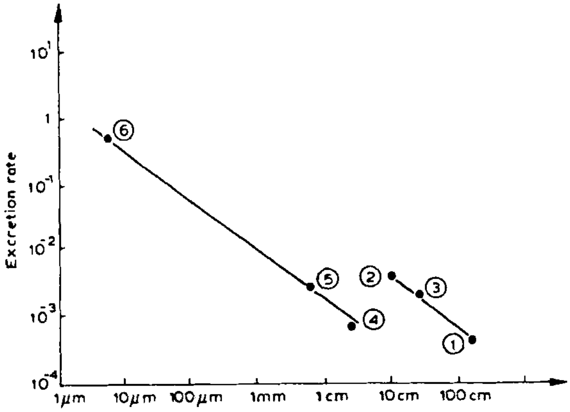

Fig. 3.12. Excretion of Cd ($24h^{-1}$) plotted to the length of various organisms: (1) Homo Sapiens (2) mice (3) dogs (4) oysters (5) clams (6) phytoplankton.

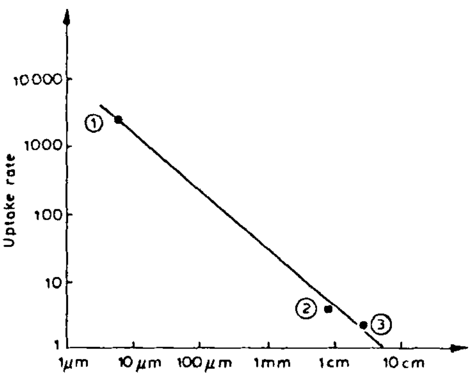

Fig 3.13. Uptake rate for Cd (µg/g 24H) plotted to the length of various organisms: (1) phytoplankton (2) clams (3) oyster.

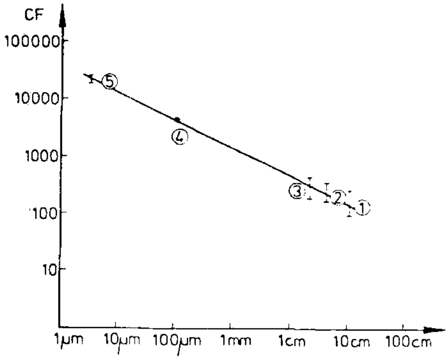

Fig. 3.14. CF for Cd versus size: (1) goldfish (2) mussels (3) shrimps (4) zooplankton (5) algae.

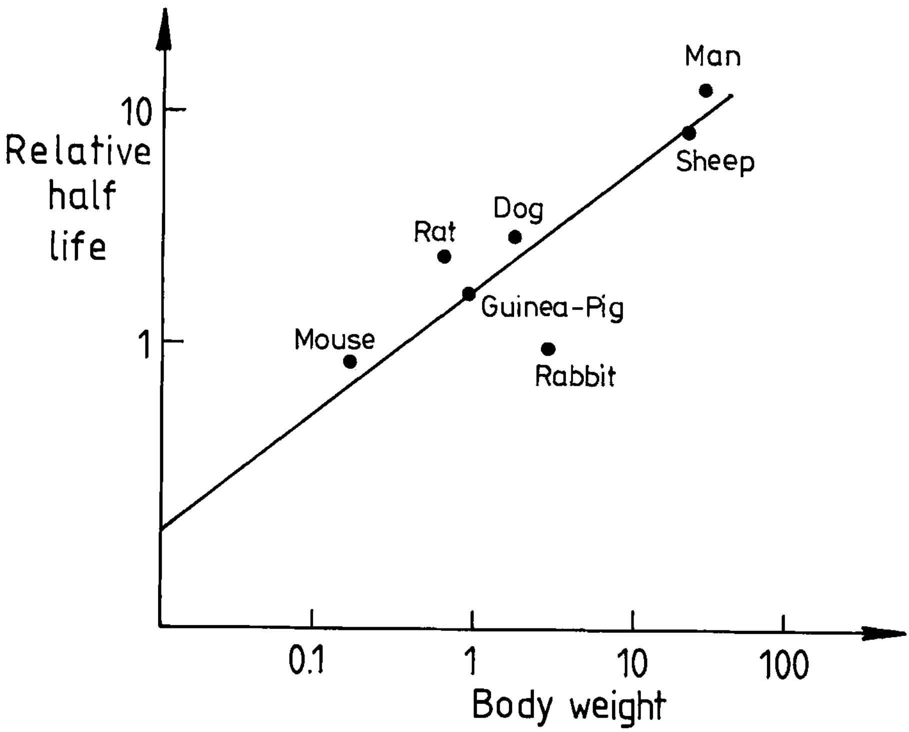

Fig. 3.15. Excretion of PCB and DDT versus organism size.

The principles illustrated in Figs. 3.12-3.16 can be applied generally. In other words, it is possible to find the uptake - and excretion rates and the concentration factors, provided that these parameters are available for the considered element or compound for one - but preferably several species. When a plot similar to Figs 3.12-3.16 is constructed, it is possible to read off the parameters when the size of the organism is known.

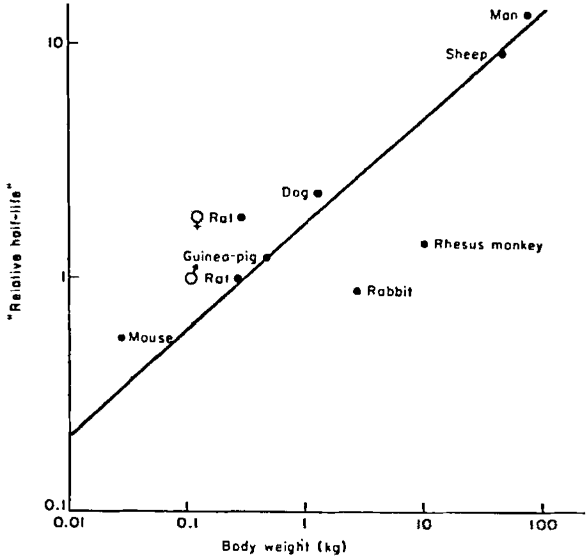

Fig. 3.16. The half life for various toxic substances relative to the half life time for rats.

There is a fixed upper limit to the total biomass of any species that can be supported in a given habitat. This fixed limit is referred to as the *carrying capacity* of that particular habitat for a particular species.

P.3.8. The carrying capacity is related to the organism size in a similar manner to energy flow rates:

$$C = w \cdot p^{3/2} \tag{3.7}$$

where C is the carrying capacity, w is the mean weight of individuals and p is the population density (White and Herper, 1970).

This means, since C is fixed, that we can increase the mean weight of the plants in a population or the population density, but not both. Space itself can be considered an important resource, independently of any other resources. Increasing the space per individual may have beneficial effects, even where other resources remain constant. The influence of space on the number of species is discussed in section 4.5 and a relationship is presented in P.4.24.

Any self-sustaining ecosystem will contain a wide spectrum of organisms ranging in size from tiny microbes to large animals and plants. The small organisms account in most cases for most of the respiration (energy turnover), whereas the larger organisms comprise most of the biomass.

Different species have very different types of energy use to maintain their biomass. For example the blue whale uses most (97%) of the energy available for increasing the biomass (G in Fig. 3.6) for growth and only 3% for reproduction. Many fishes, insects and other invertebrates use another partition of this energy. The adult female reproduces every season she is alive and the proportion going into reproduction can be over 50%.

Ecological energy flows are very sensitive to man's impact on ecosystems. A detailed picture of the energy flow in an ecosystem like that shown in Fig. 3.4 is a very useful tool for understanding this influence. The function of the ecosystem is closely related to the energy flow, and any change in the flow will mean a change in ecological function.

Fig. 3.17 shows the energy flow in a man-made ecosystem. By comparison with Fig. 3.4 it can be seen that the energy flow is simpler than in the natural system. Man-made ecosystems (chiefly agriculture systems) often have little ecological diversity (see also sections 4.5 and 4.8), in other words the number of species is small. In many cases, however, this renders the ecosystem very sensitive or vulnerable to any change.

P.3.9. Man's influence on an ecosystem quite often means a simplification or decrease in its complexity, although the relationship between an ecosystem's stability and complexity is rather complicated (see sections 4.6 and 4.8).

Such an influence may have disatrous consequences for the stability of the ecosystem (see sections 4.6 and 4.8).

Generalizations such as these must, however, be used *very carefully*, as ecological stability is a very abused concept. See also sections 4.5 and 4.8.

A total energy balance for a terrestrial ecosystem can be set up by use of the first law of thermodynamics (P.3.1.):

R + C + H + ¥ * E = O (3.8)

where R is the net radiation, C is the conduction in solids, H is the convection in moving fluids and ¥ * E is the latent heat exchange associated with evaporation. C, H and ¥ * E are negative.
Net radiation is the dominant term in the equation. It is the balance between incoming and outgoing fluxes of shortwave and longwave radiation. R can be

found from:

$$R = (1\text{-}r)\,G + é(L\text{-}\partial T^4) \qquad (3.9)$$

where G and L are incoming fluxes of shortwave and longwave radiation, respectively; ∂ is a constant (= 81.7 * 10^{-12} for R in 1y min^{-1}), r is the reflectivity coefficient, é the emissivity coefficient and T the absolute temperature. r, é and T are ecosystem surface characteristics. Generally é≈ 1 for natural mineral and organic surfaces, while r, expressed as a percentage (= albedo), varies widely, see Table 3.11.
Table 3.12 shows the energy - and water budget for land areas of the earth.

TABLE 3.11
Typical albedoes for some natural surfaces

Surface	Description; conditions		Albedo
Water			
Liquid	Solar altitude:	60^o	5
		30^o	10
		20^o	15
		10^o	35
		5^o	60
Solid	Fresh snow		75
	Old snow		50
	Glacier ice		30
Ground			
Soil	Dark organic		10
	Clay		20
	Light sandy		30
Sand	Gray:	wet	10
		dry	20
	White:	wet	25
		dry	35
Rock	Sandstone spoil, dry		20
	Black coal spoil, dry		5
Vegetation			
Grass	Typical field:	green	20
		dry	30
	Dry steppe		25
	Tundra, heather		15
Crops	Cereals, tobacco		25
	Cotton, potato		20
	Sugar cane		15
Trees	Rain forest		15
	Eucalyptus		20
	Red pine forest		10
	Hardwoods in leaf		18

TABLE 3.12
Mean values of the components of water and energy budgets for land areas of the earth.

Latitude (degrees)	Water budget (mm yr-1) P	Q	E	Energy budget (kly yr^{-1}) lE	H	R
Polar (N)	176	-106	- 70	- 4	4	0
70-60	428	-227	- 201	-12	- 8	20
60-50	577	-259	- 318	-19	-11	30
50-40	535	-155	- 380	-22	-23	45
40-30	534	-122	- 412	-24	-36	60
30-20	611	-245	- 366	-21	-48	69
Tropics (N)	1,292	-436	- 856	-50	-22	72
Tropics (S)	1,576	-546	-1,030	-60	-13	73
20-30	564	- 88	- 476	-28	-42	70
30-40	660	-165	- 495	-29	-33	62
40-50	1,302	-914	- 388	-23	-18	41
50-60	993	-605	- 388	-23	- 8	31
60-70	429	-369	- 60	- 4	- 9	13
Polar (S)	148	-120	- 28	- 2	6	- 4

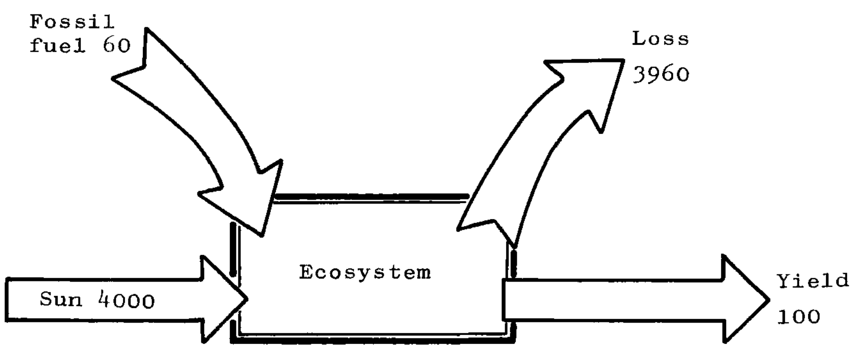

Fig. 3.17. Man-made (man-controlled) ecosystem (agriculture). Numbers in kcal $m^{-2}day^{-1}$.

3.5. ENERGY CONSUMPTION AND THE GLOBAL ENERGY BALANCE.

Recently the subjects of climate change and, particularly, the possible effects of CO_2 (carbon dioxide) on the climate are being widely discussed. Currently the question of interaction between atmospheric carbon dioxide and climate is a very critical one, that could greatly affect future energy strategies.

In 1975 the world primary consumption was about 7.6 TW, and the share of oil and gas 5.5 TW (Häfele, 1978). IIASA made an estimate of the future minimum energy demands based on the following considerations: The world is divided into seven regions roughly corresponding to North America, the Soviet Union and Eastern European countries, Western Europe, Australia and Japan, Central and South America, South East Asia and Africa, the Middle East and China.

Taking Keyfitz's population figures (1977), a total world population for 2030 not larger than 8 billion people is projected. The per capita energy demand growth rate in developed regions is assumed to decline steadily, coming close to saturation point 50 years from now, while higher growth rates and later saturation points are assumed for developing countries. A summary of this prediction is given Table 3.13.

TABLE 3.13
Demand scenario in the year 2030

Region	Population (10^6)	kW/capita	TW
North America	310	16.5	5.0
Soviet Union and Eastern Europe	460	11.6	5.3
Western Europe, Japan and Australia	780	10.5	8.2
Central and South America	720	3.3	2.4
South East Asia and Africa	3700	1.4	5.2
Middle East	300	4.8	1.4
China	1800	4.6	8.3
Total	8070	average: 4.4	35.8

This scenario gives a total global energy demand of 35 TW or almost 5 times present energy consumption. The average energy consumption is predicted at 4.4 kW per capita in 2030, while only 28 developed countries today have an energy consumption larger than 2 kW. The cumulated overall world energy demand by 2030 will be approximately 1000 TW for this reference scenario. The crucial questions are: can we meet the demand for such a high energy consumption? If so, how, and what will the environmental consequences be?

Another problem is of course the size of available fossil energy resources needed to supply this large energy demand. Fig. 3.18 lists the economically recoverable reserves of fossil energy and predict that in 2030 only a fraction of the 35 TW can be supplied in the form of conventional oil, gas and coal. The geological resources of fossil energy are much larger, but cannot be recovered under present and predicted technological and economic conditions.

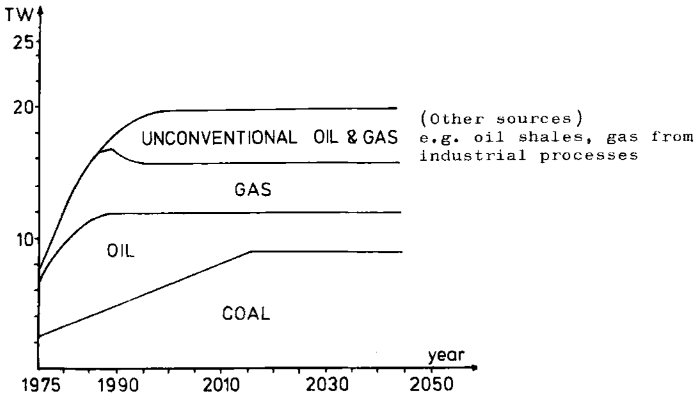

Fig. 3.18. Economically recoverable reserves of fossil energy.

A further constraint on the massive consumption of fossil fuel is represented by the CO_2 problem. And what we are considering here is: how such large scale use of fossil fuel would influence the global climate?

The use of fossil fuel means the oxidation of carbon or carbon hydrides, which produces a stoichiometric amount of carbon dioxide:

$$C + O_2 \rightarrow CO_2 \quad (3.10)$$

$$C_xH_y + (x + y/4)O_2 \rightarrow 1/2\, y\, H_2O + xCO_2 \quad (3.11)$$

Having determined that the burning of fossil fuels produces carbon dioxide, we can next consider how this carbon dioxide (and watervapour) produced by oxidation will influence the climate.

This is a very complex question and any attempt to an answer requires a comprehensive knowledge of the global cycle.

Another crucial issue related to the long-term prediction model, is the estimation of the ultimate recovery of coal, oil and natural gas. Zimen (1978) assumes a final input of carbon dioxide from fossil sources into the atmosphere to be 8 times the preindustrial amount of atmospheric carbon dioxide, taken as 292 ppm or $52.1 \cdot 10^{15}$ moles. Baes et al. (1976 and 1977) estimate this figure to be 12 times as great, while Perry et al. (1977) take the figure to be 8.2 times. Table 3.14 gives the most recent estimates of global fossil fuel resources and the corresponding amounts of carbon dioxide that would be produced, calculated from the following information (Ziemen, 1977):

Coal 2.00 moles of carbon dioxide per MJ
Oil 1.68 moles of carbon dioxide per MJ
Gas 1.29 moles of carbon dioxide per MJ

TABLE 3.14
Recent estimates of global fossil fuel resources and the corresponding amount of carbon dioxide expressed as 10^{15} moles

	Estimates of global fossil fuel resources	
	10^{21} J	10^{15} mol CO_2
Solid fuel	150 - 300	300 - 600
Liquid fuel	10 - 80	15 - 130
Tars and shales	10 - 20	17 - 35
Natural gas	4 - 44	5 - 55

Rotty (1978) has suggested several possible patterns of future carbon dioxide production by use of the following expression:

$$\frac{1}{N} \cdot \frac{dN}{dt} = 0.043 \left(1 - \frac{N}{A}\right)^x \qquad (3.12)$$

where

N is a function of time t and represents the total cumulative amount of carbon dioxide produced by use of fossil fuel up to the time t. A is the amount of carbon dioxide that would be produced from all of the fossil fuel ultimately recoverable (corresponds to $7.3 \cdot 10^{12}$t C). x is a parameter applied to vary the emphasis on price, availability etc, as the fraction of recoverable fossil fuel remaining is reduced.

Fig. 3.19 shows the annual production of carbon dioxide expressed as ppm per annum plotted against time for 3 different values of x.

Fig 3.20 gives the corresponding cumulative carbon dioxide production.

This model is, of course, very simple and does not consider the many interacting processes of the global carbon dioxide cycle (see 2.5).

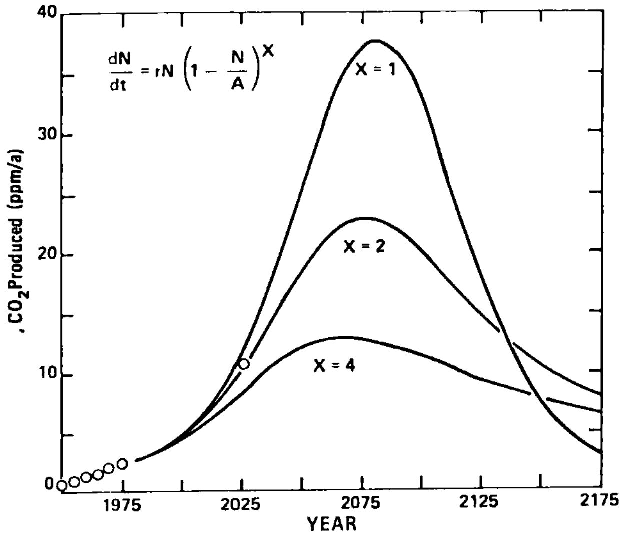

Fig. 3.19. Global production of CO_2 from fossil fuels.

One part of the problem is the problem is the quantitative determination of the carbon pools and the fluxes between these pools, another is the relationship between the atmospheric carbon dioxide concentration and the climate. This issue is also very complex as different subsystems interact with each other.

The global climatic system consists of 5 subsystems: the atmosphere, the oceans, the cryosphere (ice and snow), the land surface and the biosphere. These subsystems interact with each other through a wide variety of processes. The climatic state (Garp, 1975) is defined as the average and the variability of the complete set of atmospheric, hydrospheric and cryospheric variables over a specified time interval and in an specified domain of the earth-atmosphere system. The climatic states are subject to fluctuations of a statistical origin in addition to those of a physical nature. These statistical fluctuations in the weather are unpredictable over the time scales of climatological interest and are therefore referred to as "noise" or the "inherent variability of the climatic system".

With reference to the carbon dioxide problem, we are not concerned with the inherent variability of the climate, but with the natural variability caused by changes in external and/or internal conditions. However, any estimate of a change in climate caused by an increase in carbon dioxide concentration must take into consideration the fact that climate fluctuates naturally with time, and therefore that it takes a long time to detect a significant change in climate. It should also be pointed out that problems could arise because of the time scales of natural variability, e.g. the time constant for heat storage in the oceans.

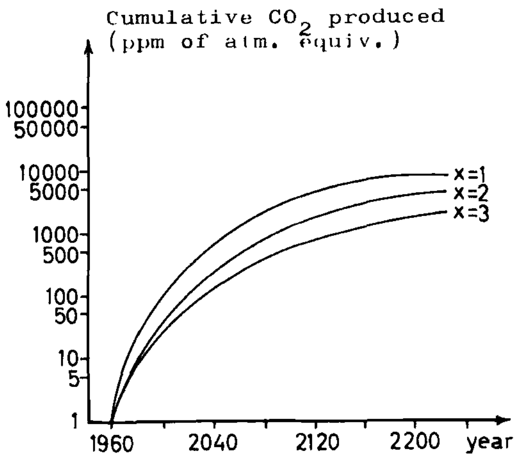

Fig. 3.20. Projected cumulative CO_2 production for x=1, 2 and 3 (for formula, see text).

A global average model can be used to compute a change in average climate for a given change in atmospheric carbon dioxide concentration. Such models are available today, although results are uncertain due to lack of knowledge of feedback mechanisms.

The question of regional climatic changes is, however, of more practical importance. In this context it should be stressed that

P.3.10. it is possible to have drastic changes in the regional climate without any substantial change in the global average situation.

This is illustrated in Fig. 3.21, where changes in seasonal temperatures are plotted against latitude.

The global energy balance (see Fig. 3.22), is influenced by the carbon dioxide concentration in the atmosphere. The atmosphere is transparent for solar radiation, but prevents, to a certain extent the loss of heat from the earth's surface (by longwave radiation). The radiation balance of the atmosphere is essentially determined by the presence of optically active minor constituents, such as water vapor, carbon dioxide, ozone, aerosols and others. An increased carbon dioxide concentration means increased absorption of longwave radiation and consequently an increased global average temperature. Carbon dioxide has what is called a greenhouse effect, but the atmosphere also contains a number of other minor constituents capable of causing changes in the global average temperature. Table 3.15 lists the calculated surface temperature change for a 1% increase in each of the parameters given (the table is based upon the following sources: Reck, 1978; Wang et al., 1976; Reck et al., 1977; Ramathan, 1975; Hummel et al., 1978). However, from this table it can be seen that the concentration of carbon dioxide seems to be the most important agent in this respect, although the role of trace gases has not yet been investigated in detail.

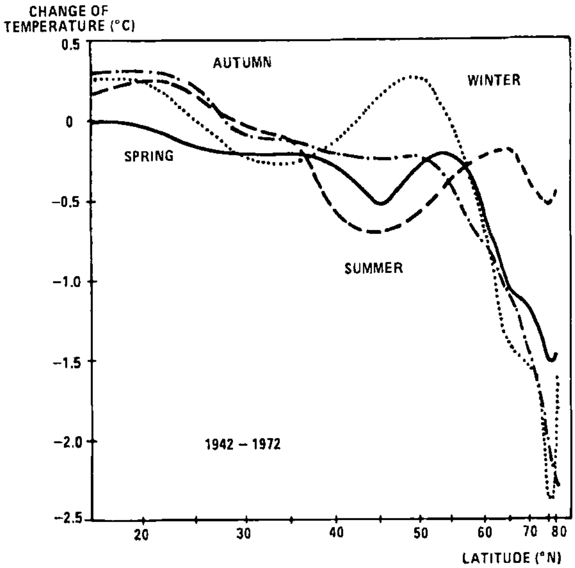

Fig. 3.21. Meridional profile of the change in each season of zonal mean temperature (°C) during the period 1942-1972. (Source: Williams 1976)

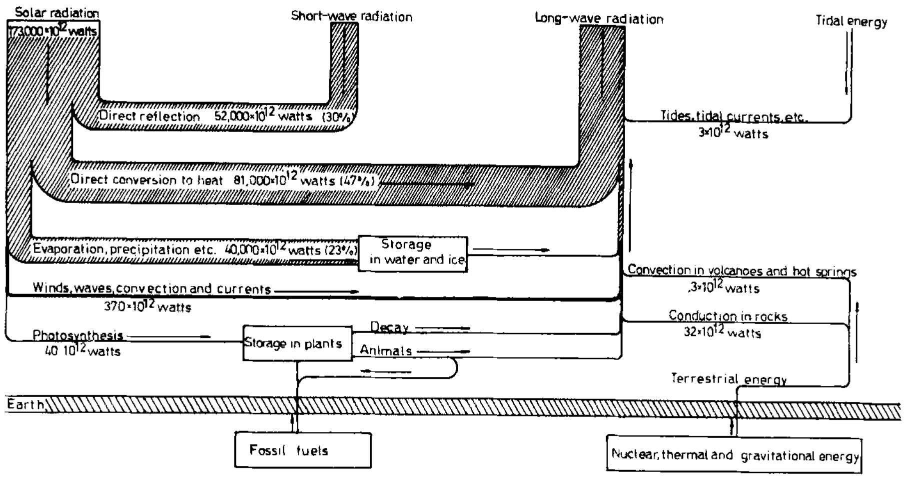

Fig. 3.22. The global energy balance. More than 99% of the input is solar radiation.

TABLE 3.15
Calculated surface temperature change for a 1% increase in each of the parameters given

	Present value	Units	ΔT_s	Relative rank
Albedo	14.01	%	-0.14	1
Relative humidity	74	%	0.065	0.46
CO_2	330	ppmv	0.020	0.14
Airborne paticles extraction coefficient	0.1	km^{-1}	-0.0063	0.057
N_2O	637	ppbv	0.0044	0.031
O_3	0.37	atm-cm	-0.0032	0.023
CH_4	1.6	ppmv	0.002	0.014
H_2S	3.5	ppmv	0.0012	0.0086
$CHCL_3$	<2 $*10^{-4}$	ppmv	0.0010	0.0071
NH_3	6 $*10^{-3}$	ppmv	0.0009	0.006
HNO_3	10^{-3} - 10^{-2}	ppmv	0.00060	0.004
$CFCl_3$	2.3 $*10^{-4}$	ppmv	0.00035	0.0025
SO_2	2	ppmv	0.00020	0.0014
CF_2Cl_2	1.3 $*10^{-4}$	ppmv	0.00019	0.0014
C_2H_4	2 $*10^{-4}$	ppmv	0.0001	0.0007
CH_3Cl	5 $*10^{-4}$	ppmv	0.0001	0.0007
CCl_4	1 $*10^{-4}$	ppmv	0.0001	0.0007

ΔT_S = surface temperature change (K) for 1% increase in the present average value

Augustsson et al. (1977) have calculated the relationship between the atmospheric carbon dioxide concentration and the surface temperature of the earth, see Fig. 3.23. Changes in cloud cover can be taken into account by assuming either a fixed cloud top altitude (CTA) or a fixed cloud top temperature (CTT). Both assumptions are taken into consideration in Fig. 3.23, but even if the concentration of carbon dioxide could be accurately predicted, vast uncertainties about its effect on the climate would remain. However, there is strong evidence to suggest that additional atmospheric carbon dioxide will cause global warming in the range of an average 2 to 4 °C rise in temperature for a doubling in the carbon dioxide concentration.

As well as the global average surface temperature the atmospheric circulation pattern is also affected. The general atmospheric circulation is characterized by a poleward transport of heat energy. The general temperature increase caused by a higher carbon dioxide concentration enhances the poleward transport of latent heat in middle latitudes, resulting in a general movement of agroclimatic zones. For example, summer temperatures may become too high for corn and soybean, so that the corn belt will be shifted north.

Agricultural productivity is very much dependent upon climate. Each crop has its unique response to climatic variations (Thompson, 1975), as can be seen in Tables 3.16-3.17

TABLE 3.16
Estimated percent change in corn yield due to changes in temperature and precipitation. Source: Benci et al. (1975)

Temperature change (°C)	Change in precipitation (% of normal)				
	- 20%	- 10%	0	+ 10%	+ 20%
- 2.0	19.8	21.2	22.7	24.2	25.6
- 1.0	8.4	9.8	11.3	12.8	14.2
0	- 2.9	- 1.5	0	1.5	2.9
+ 1.0	-14.2	-12.8	-11.3	- 9.8	- 8.4
+ 2.0	-25.6	-24.2	-22.7	-21.2	-19.8

The response of snow and ice cover to climatic factors varies greatly in time. Typical extents of cover are 0.1-1.0 years for seasonal snow, 1.0-10 years for sea ice and 1000-100,000 years for ground ice and ice sheets. Of primary interest, of course, are the times of seasonal temperature transition across the 0°C threshold (-1.8 °C for seawater). Another important effect is the large albedo differences between snow cover (appr. 0.8) and snow-free ground (0.1-0.25) or between ice (0.65) and water (0.05-0.1). At present perennial ice covers 7% of the world's oceans and 11% of the land surface (see Table 3.18), with a further percentage of land under seasonal snow cover (see Table 3.18). Barry (1978) has attempted to predict the effect on the cryosphere of a doubling in the atmospheric carbon dioxide concentration, assuming that it will result in a global warming of 1.5°C with a rise of 5-6°C in polar latitudes (Manabe et al., 1975).

TABLE 3.17
Percent deviation from world rice production base as influenced by changes in temperature and precipitation

Precipitation change (%)	Temperature change (°C)						Total precipitation change (%)
	-2	-1	-0.5	+0.5	+1	+2	
-15	-19	-13	- 8	- 4	0	3	- 8
-10	-17	-11	- 6	- 2	2	5	- 6
- 5	-13	- 7	- 2	2	6	9	- 2
+ 5	- 9	- 3	2	6	10	13	2
+10	- 5	1	6	10	14	17	6
+15	- 3	3	8	12	16	19	8
Total temperature change	- 11	- 5	0	4	8	11	

Source: Stansel and Huke (1975)

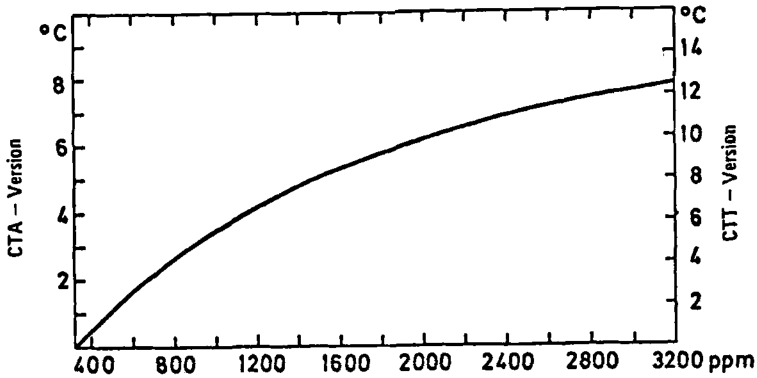

Fig. 3.23. CO_2 concentration and equivalent surface temperature. Augustsson and Ramanathan model.

TABLE 3.18
Components of the cryosphere (Untersteiner (1975); Kukla et al. (1974))

	Area (10^8 km^2)	Volume (10^8 km^3 as water)

Land ice	0.16	0.31
Antarctica	0.138	0.28
Greenland	0.018	0.027
Other areas	0.004	0.003
Ground ice (excl. Antarctica)	0.248	<0.025
Cont. permafrost	0.075	<0.02
Discont. permafrost	0.173	<0.005
Sea ice		
Antarctica - September	0.20	
Antarctica - March	0.025	
Arctic - September	0.054	
Arctic - March	0.15	
Total snow, land ice, sea ice		
N. hemisphere - January	0.58	
N. hemisphere - July	0.14	
S. hemisphere - January	0.18	
S. hemisphere - July	0.25	
Global		
mean annual	0.59	

It is concluded that:

1. there will be negligible changes for major ice sheets and ground ice on a time scale of centuries,
2. changes in seasonal snow cover may also be minimal. Any increase in winter snowfall would probably be offset by increased summer melt,
3. it is possible that greater melt of pack ice leading to more open water, would reduce the solar radiation input.

However, it is also concluded that major deficiencies exist in terms of data on snow cover extent and depth. Many crucial research problems remain, especially because our knowledge about the effects of a rise in temperature on the melting glaciers and ice sheets is rather limited.

Although much more research is needed before we can map the relationship between the consumption of fossil fuel and the climatic conditions, it can be concluded from this brief review that we have quantitative knowledge of the interactions between the subsystems to justify constructing a model of this relationship. It is only through the use of such a model that we can assess in which direction we should conduct our further research to discover ways of setting up more reliable models.

The problem discussed in this chapter is a very complex one, because its solution requires knowledge of the interactions between a large number of subsystems. A break-down of the problem is attempted in Fig. 3.24: the energy policy determines the energy demand and both determine the consumption of fossil fuel, which in turn is related to carbon dioxide production.

The concentration of carbon dioxide in the atmosphere is a function of both the global carbon cycle including all its processes, and the carbon dioxide production. The carbon dioxide concentration and the global average surface temperature are related in a very complex way, and the latter will cause several other global changes, such as higher sea level, shifts in crop belts etc - changes, which it is very difficult to predict with our present knowledge. However, such predictions of global changes are needed before we can set up a realistic energy policy.

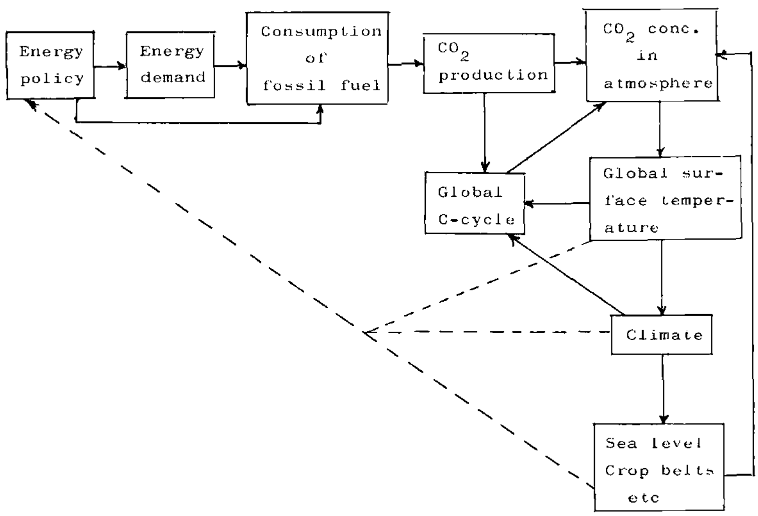

Fig. 3.24. A break-down of the CO_2-problem into subsystems. Interactions between the subsystems are shown.

3.6. ENERGY BUDGETS OF ANIMALS AND PLANTS.

P.3.11. An animal is coupled to the climate surrounding it by energy flow.

Animals are often in transient states for limited periods of time, but over a sufficiently long time interval they must be in an energy balance. Warm blooded animals (homeothermic) require a more or less constant body temperature, while cold blooded (poikilothermic) animals can allow their body temperature to vary over a considerable range. However, the principles of energy balance in physical terms are essentially the same for warm blooded and cold blooded animals.

The principle of an energy balance for food is shown in Fig. 3.6 but it might also be considered as an illustration of a mass balance, as mass can be converted to energy by multiplying it by the content of chemical energy per g of dry matter (expressed e.g. in the unit kJ g^{-1}). Within the animal metabolic heat is generated from food consumed and additional energy is acquired by absorption of incident radiation, in the form of direct sunlight, scattered skylight, reflected light from clouds and other surfaces, and thermal radiant heat from the environment.

The energy balance for the surface of an animal can be expressed as follows:

$$M - E + R = \acute{e} \partial T_s^4 + k * V^{1/3} \bullet D^{-2/3} (T_s - T_a) + C \qquad (3.13)$$

where

M = metabolic heat
E = evaporation
R = radiation absorbed
é = emissivity of the surface
∂ = Stefan-Boltzmann's constant
T_s = surface temperature in K
k = a constant
V = wind speed
D = diameter of body (cm)
T_a = air temperature in K
C = energy exchange by conduction

The rate at which metabolic heat flows out from the body through the insulating layer of fat, fur or feathers depends on the temperature gradient between the body temperature and the surface temperature. Hence, the rate of net heat production M-E is given by:

$$M - E = \frac{T_b - T_s}{I_b + I_f} + \frac{T_b - T_s}{I} \qquad (3.14)$$

where
T_b = body temperature
I_b = insulation quality by fat
I_f = insulation quality by fure (feather)
$I = I_b + I_f$

By eliminating M-E from the two equations (3.13) and (3.14) we get:

$$T_b - T_s = I(\acute{e}\partial \bullet T_s^4 - R + k \bullet V^{1/3} \bullet D^{-2/3} (T_s - T_a)) \qquad (3.15)$$

If T_b is fixed, as in homeotherms, the surface temperature T_s will adjust, so the equation is valid. For poikilotherms the body temperature will adjust to the surface temperature through the animals' insulation mechanisms, see equation (3.14). If M-E is very small, as it often is for some reptiles, then T_b and T_s are almost equal. R is of course a very complicated function for the animals in the open, particularly during the day time. However, with some approximations we have:

$$R = \acute{e}\partial \bullet T_a^4 \qquad (3.16)$$

The climate also has a pronounced effect on plants. If the air is cooler than the leaf surface, then the flow of air across the leaf surface will pick up heat from the leaf and carry away a definite amount of energy by means of convection. It the air is warmer than the leaf then there is an energy transfer from the air to the leaf. The larger the leaf, the thicker the boundary layer of air which adheres to the leaf surface. Therefore, the rate of heat transfer is inversely proportional to leaf size. Furthermore, the convection is proportional to the difference in temperature between leaf and air and varies directly with the square root of the wind speed.

A leaf surface absorbs a total amount of radiation and get rid of energy by reradiation.

If a leaf loses energy by radiation and convection, we can set up an energy balance as follows:

$$R = \partial T^4 + 6 \bullet 10^{-3} \sqrt{V} * D^{-1} (T - T_a) \qquad (3.17)$$

where
V = the wind speed
D = the width of leaf (cm)
T_a = the plant temperature

If we add the plant's ability to cool by transpiration, the leaf temperature is reduced further as demonstrated in Table 3.19. The energy budget equation involving transpiration in addition to radiation and convection is expressed:

$$R = \partial T^4 + 6 * 10^{-3} \sqrt{V} \bullet D^{-1} (T - T_a) + 580 \frac{d - rh \bullet d_a}{r_e + r_a} \quad (3.18)$$

where

d = saturation concentration of water ($g\ cm^{-3}$) in the leaf

d_a = saturation concentration of water ($g\ cm^{-3}$) in the air

rh = relative humidity

r_e = resistance of the leaf to water loss

r_a = resistance of the leaf surface (boundary layer) to water loss

TABLE 3.19
Characteristic temperatures in degrees centrigrade for the conditions listed (°C)

R ($cal\ cm^{-2}\ min^{-1}$)	Radiation only	Radiation and convection $V = cm\ sec^{-1}$			Radiation, convection and transpiration $V = cm\ sec^{-1}$		
		10	100	500	10	100	500
0.6	20	28	29	30	25	27	29
1.0	60	41	34	32	33	31	30
1.4	89	53	39	34	40	35	32

A modification of the normal energy balance for plants is widely used in agriculture. The heat load can be increased by use of heat trapping, as demonstrated in Fig. 3.25. This is the most widely used form of control in plant environments. Other possibilities are summarized in Table 3.20.

TABLE 3.20
Artificial control of plant environment

Control practice	Major beneficial results	Major adverse result
Heat trapping	Higher plant temperature	Too high plant temperature
Shading	Lower plant temperature in hot weather	Expensive
Flooding	Frost protection	Retarded warming after cold spell
Spraying cold water	Frost protection	Expensive
Burning fuels	Frost protection	Expensive
Wind machines	Frost protection	Expensive
Soil heating cables	Frost protection	Very expensive
Hot capping	Higher plant tempe- rature	Very expensive
Mulching and plowing	Reduced water loss	Increased frost hazard
Irrigation	Reduced moisture stress	May benefit soilborne pests
Soil packing	Frost protection	Retard soil warming
Shelter belts and nurse crops	Reduce heat loss and erosion in spring	Soil moisture losses from deeper layers

Daily temperature patterns are also modified by topography. A slope facing the sun intercepts light beams more perpendicularly than does a slope facing away from it; as a result a South-facing slope in the Northern hemisphere receives more solar energy than a North-facing slope and heats up faster and gets hotter during the day (see Fig. 3.26). A South-facing slope is typically drier than a North-facing one, because it receives more solar energy, and therefore more water is evaporated.

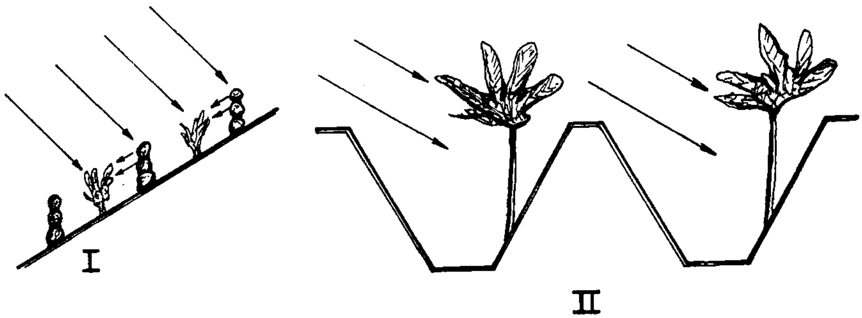

Fig. 3.25.. Heat trapping by stone walls between crop rows (I) and by furrow planting (II).

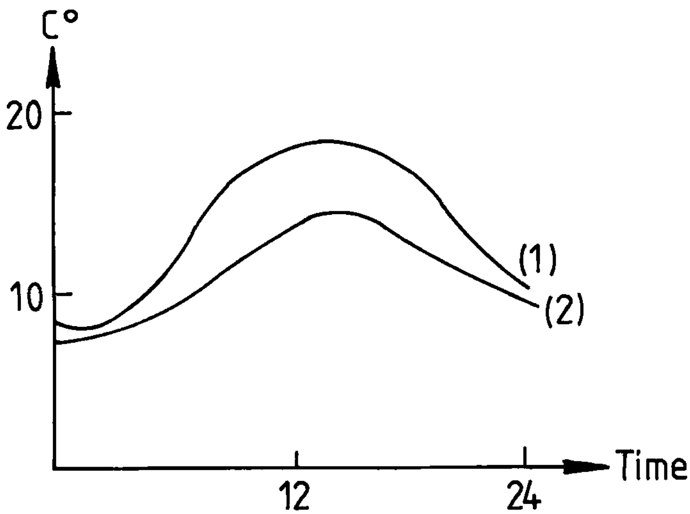

Fig. 3.26. Daily variations of temperature on an exposed South-facing slope (1) and a North-facing slope (2) during late summer in the Northern hemisphere.

QUESTIONS AND PROBLEMS.

1. Draw all possible parallels between a foodchain and an energy chain.

2. List at least 6 environmental factors, which influence the primary productivity.

3. Use Fig. 3.4 to answer the following question: If algae have a concentration factor of 1,000 relative to water containing 1 $\mu g\ l^{-1}$ of a toxic and completely non-biodegradable compound, what will be the concentration of the toxic compound in carnivores and microorganisms, provided that the uptake efficiency from food is 90% and that no excretion takes place?

4. Find the approximate generation time, metabolic rate and intrinsic rate for a homeothermic animal with a length of 20 cm.

5. How would an increasing humidity influence the global average temperature? What would be the temperature change for an increase form the present humidity of 74% to 80%, and how would such a change influence the corn yield and cryosphere?

6. What will be the sign of entropy change for denaturation of proteins?

7. Discuss the connection between the second law of thermodynamics and the ecological energy pyramid.

8. A chlorphenol has a solubility in water of 1.2 mg l^{-1}. Find the approximate concentration factor for mussels by use of the methods presented in sections 2.13 and 3.4.

9. What would be the expected increase in surface temperature if 10% of the earth's surface area now covered by snow and ice becomes tundra? Use Tables 3.11 and 3.15.