CHAPTER 3

Environmental Concerns

A. INTRODUCTION

From the commencement of its work, SCOPE recognized that environmental issues could be classified in several ways:

(a) by sectors (e.g., air, land, sea, freshwaters);

(b) by biomes (e.g., tundra, forest, desert, grassland);

(c) by processes (e.g., pollution, desertification, competition); and

(d) by the nature of human response or approach to them (e.g., monitoring, modelling, standard setting, resource planning).

No single classification is appropriate to all circumstances. The choice usually depends on the purposes for which the information is assembled and analysed. For this part of the report, which presents detailed information about the activities in the Mid-term Programme of SCOPE and reviews the wider interests of the ICSU Unions, Commissions, and Committees, a two-way matrix (Figure 1) has been drawn up as an overall framework.

The present chapter on Environmental Concerns reports on the topics forming the first axis of the matrix: biogeochemical cycles (including the cycles of substances whose levels in the biosphere have been changed by man), pollutants, and ecosystems (and their response to interference). The reports on biogeochemical cycles emerge from Project I in SCOPE's Mid-term Programme, those on ecosystems from Project II, and those on pollutants from Project IV. In addition, a section on climate and its possible disturbance by man has been inserted because of the contemporary interest of the subject and its fundamental importance to biological processes. The boxes for 'non-renewable natural resources' and 'human ecology' are included in the matrix as an indication of the importance of those fields, but SCOPE has not undertaken specific studies that can be grouped here and no special section dealing with them has been prepared.

Part of Chapter 1 refers to the need for wise use of non-renewable resources such as fuels, soils, or agricultural land. By and large, the management of non-renewable resources is a matter of economics and book-keeping. It is important to conduct thorough surveys to define the scale of the resource and to evaluate the environmental and social implications of alternative patterns of resource use.

Concerns / Responses	Climate	Biogeochemical Cycles	Pollutants	Ecosystems	Non-renewals Natural Resources	Human Ecology
Problem Identification and Monitoring						
Modelling						
Risk Estimation						
Evaluation and Communication						
Standard Setting Social Policy						

Figure 1 Matrix classification of environmental issues

Exploitation tends to concentrate on the cheapest available reserves of raw materials or energy. If demand is sustained or grows as rich sources are fully utilized and depleted, the value of poorer or substitute resources rises and their exploitation becomes economically viable. Ultimately, a disproportionate amount of effort, cost, and energy may be absorbed if a demand is to be met, but this in itself tends to apply economic brakes to further exploitation and provides an incentive for use of substitute materials, energy sources, or recycling. In the energy field, for example, projected exhaustion or inadequacy of fossil fuel reserves has stimulated nuclear power development, and worries over the attendant scientific, technical, and environmental problems (such as the disposal of plutonium wastes) have led in turn to proposals to pursue solar, geothermal, and other sources of energy. Probably the world's energy future will involve a variety of sources, in different proportions at different places and times. Rising costs and demands for high standards of safety and environmental quality will be likely to promote energy-conserving processes and reduced use. These matters extend beyond SCOPE's field, but there is a continuing role for the scientist in the estimation of reserves of resources (other ICSU bodies are concerned with aspects of this), and the analysis of the environmental implications of alternative systems of production and utilization. These topics are discussed further in Chapter 6.

Similarly, the present chapter does not contain a detailed report on human ecology, although the report on SCOPE Mid-term Project III on Environmental Aspects of Human Settlements, in Chapter 4, is relevant here. Population issues are discussed generally in Chapter 1, and the role of the scientific community in their study is referred to in Chapter 6. There are other gaps within the sections: noise, for example, although a pollutant causing increasing concern, has been the concern of IUPAP and there is nothing on food (including the development of new and unconventional food sources like those studied in the Use and Management section of IBP). All these could have been considered if resources had been available to SCOPE. Many, however, are the concern of WHO, FAO, and other ICSU committees or unions (see Chapter 5 and Appendix 3).

It is inevitable that many overlaps occur and that wide-ranging projects may fall partly under one heading and partly under another. The report on human settlements is one example: that on pollutants, which also provides information vital to risk estimation, is another. There are obvious affinities between the detailed study of the analysis and modelling of successional change in terrestrial vegetation included in this chapter and that on the general theme of simulation modelling (Project V in the SCOPE Mid-term Programme) in Chapter 4. Figure 1 should be used as a general guide to both chapters, and has relevance to the analysis of the environmental work of ICSU described in Chapter 5.

B. BIOGEOCHEMICAL CYCLES

1. Introduction

As Chapter 1 pointed out, human economic activities are now affecting all the main components of the biosphere. The atmosphere, hydrosphere, soil cover, and all living organisms are affected in a great variety of ways, and even the earth's crust is increasingly modified by mining, oil exploitation, and other operations. Some of these activities have a potential impact that has not been fully appreciated. For example, the complete deforestation of large areas and the extension of ploughing to additional tracts of natural grassland may lead to a decline in total world biomass as well as to the impoverishment of the flora and fauna in terms of species diversity. There are compensations through the reclamation and development of infertile lands, the irrigation of arid soils, and the development of increasingly productive agriculture in some places. However, these gains may be exceeded by losses in biomass or by soil deterioration and it is vitally important to measure the scale of the changes.

Modifications in the plant cover of the earth are associated with changes in global and local cycles of water which are observed in many parts of the world. Devegetation, and especially deforestation, alters the regimen of surface water and if not carefully controlled may lead to erosion as well as increased loss by evaporation. The construction of dams, canals, and irrigation schemes has altered the hydrology of the land in certain areas, intensified evaporation and has locally caused the mobilization and accumulation of salts in water and surface soil. Air pollution causes the acidification of rainfall in many areas. Mineral loading in river and lake water is, in general, increasing. The implications of these interacting changes in the water cycle need thorough evaluation.

The earth's surface is naturally a mosaic of different kinds of vegetation and fauna associated with different topographic and hydrological features. Man not only modified this initial heterogeneity but created a secondary mosaic of farms, water storage and supply systems, communication networks, towns, industries, nature reserves, national parks, and waste disposal areas. With this secondary heterogeneity are associated changes in the distribution of minerals which are mined in increasing quantities and used by industry to manufacture new compounds. The burning of fossil fuels, the ejection of dust and aerosols into the atmosphere, the extensive application of fertilizers and pesticidal sprays, and changes in cultivation systems have had a profound impact on the biogeochemical cycles of important substances and have added to the biosphere materials which were not naturally present there before the human industrial era.

A notable feature of the twentieth century is the accelerating progress of chemistry, discovering new elements and their isotopes, creating large numbers of new compounds, and disseminating the products of the chemical industry into all branches of human life. The increase in the chemical loading of the biosphere particularly affects the cycles of carbon, nitrogen, and phosphorus which are vital to the support of life. Cycles which have developed over millennia are now modified through many processes, e.g.:

(a) Increase in the nitrification of the environment.

(b) Enrichment of the environment with a wide range of carbon compounds.

(c) Increased ejection of sulphur compounds, especially into the atmosphere but returning to freshwaters in rain.

(d) The secondary acidification of the environment through sulphur and nitrogen emissions and the consequential decalcification, especially of poorly buffered water bodies.

(e) Increases in the phosphate levels of the land and freshwaters especially through fertilization but also through the increasing levels of phosphorus in treated sewage effluents.

(f) Widening contamination of areas of the environment with elements and compounds previously present only as traces. This may be a particularly significant process because the biological significance of many rare elements is not fully understood.

Reduction of soil cover is one of the more dangerous phenomena at present because the rates of production of new soils are so slow and many processes which created the existing soil cover (e.g., glaciation over much of the northern hemisphere) are not now widely operative and would themselves bring even greater disruption. Losses of soil resources, coupled with perturbations in hydrological cycles and variations in climate and in chemical contamination caused by urban and industrial processes, constitute a significant potential threat to human well-being. It is clear that natural biogeochemical processes are intimately interlinked with the effects of man's impact on the biosphere. Conversely, an understanding of biogeochemical cycles is of fundamental importance if man's impact is to be examined with a view to applying appropriate scales of regulation. This is why SCOPE, in its Mid-term Programme, attached great importance to the processes of biogeochemical cycling.

The following sections of this report describe in detail the cycles of nitrogen, phosphorus, sulphur, and carbon. In addition, SCOPE has been concerned with the way in which biogeochemical information can best be presented. The cartographic format is well suited to display information on regional patterns in the distribution of important elements; a sub-project on biogeochemical cartography was included. A workshop considered a provisional programme for geochemical cartography in which cartographic presentations would be used to show the interrelationship between biogeochemical processes and patterns at local, regional, and global scales, and the patterns of vegetation and plant productivity. In addition, the techniques would be valuable in presenting the results of monitoring background levels of biosphere elements and the distribution of materials released by man. It was suggested that the mapping of potential vegetation and the recording of modifications of existing vegetation should be undertaken alongside catalogues of the mineral composition of the more important dominant plants. This information could be related to maps of the distribution of elements, for example in stream sediments or in the soil and in annual mineral deposition and absorption. Mapping of the composition, quantities, and flow of dissolved materials would clearly be valuable in extending the process to inland waters. Mapping of the composition of rainfall would equally be important in determining inputs to the soil and vegetation and ultimately to the drainage systems.

Activities in many of these fields are in progress in a number of countries. A series of extensive biogeochemical maps has been prepared for the Soviet Union, and the composition of the sediments in stream beds has been analysed in England, Wales, and parts of Scotland. There are extensive vegetation maps, including potential vegetation, of large areas of North America.

2. Nitrogen, Phosphorus, and Sulphur

a. Man and Biogeochemical Cycles: Impacts and Problems

Nitrogen, phosphorus, and sulphur are essential elements in all living matter and are found in varying proportions to carbon, depending on the chemical nature of the compounds in which they occur. A pattern for the circulation of these elements in nature developed when microorganisms, plants, and animals appeared on earth. The pattern was set by the physical and chemical environment, by the chemical nature of these elements, and by the geographic distribution of microorganisms, plants, and animals. The appearance of *Homo sapiens* may not have had any great effect on these patterns as long as man was nomadic. That state of affairs changed when man formed settlements to which he transported vegetable matter and meat, but from which hardly any waste returned to the source areas. The effect must have been particularly noticeable for phosphorus which is scarcely leached from soils and this accumulated in the soils of the settlements and their immediate surroundings. Analysis of soil phosphate has been used in Sweden to locate archaeological settlements. It is, of course, difficult to assess the impact of such a process on the environment. Man continues to perturb the natural biogeochemical cycle today, with the difference that in some settlements a great deal of the accreted phosphorus is released into lakes and rivers. In some regions agriculture has been practised for a very long time and must have led to a sizeable depletion of phosphorus in soils; one reason for the present use of phosphorus fertilizers. The intensive cropping of small areas of woodland in Eastern England over many centuries for firewood, wattle, and building timber has led to a depletion of phosphorus levels in those soils.

Similar processes must also have occurred for nitrogen and sulphur, although their chemistry would favour leaching from soils or return to the atmosphere. Nitrophilous plants such as nettle (*Urtica dioica*) are characteristic of ground disturbed and enriched by man in some temperate areas. In arid areas, archaeological sites sometimes show accumulation of nitrate in and around former sewage dumps – as observed, for example, in prehistoric settlements in the Indus valley. Arid conditions would also lead to high nitrate concentrations in ground waters formed in settlement areas. The high nitrate concentrations observed in ground waters in the semi-arid parts of India and Africa are perhaps partly due to such human intervention in biogeochemical cycles in the past.

Man's control of plants capable of fixing atmospheric nitrogen may constitute another source of interference in the nitrogen cycle. Such control may have been exercised even before the discovery of nitrogen-fixing organisms via changing food habits and, inadvertently, by the grazing of domestic herds in virgin areas.

In order to assess man's impact on the biogeochemical cycles of nitrogen, phosphorus, and sulphur, it is necessary to define a reference state for these cycles. In view of the foregoing discussion, this may not be so simple. The most we can do – and it is clearly unsatisfactory – is to assess the impact of man's activity on these natural cycles during the last century as compared with the preindustrial state rather than with the much earlier natural state. It is possible that some of the more recent impacts of man may have been amplified by 'ancient' impacts.

A breakthrough in modern agriculture came with the invention of industrial processes for fixing atmospheric nitrogen. An almost unlimited reserve of nitrogen fertilizers is foreseen, although production may be limited by available energy. The fate of the fixed nitrogen has only recently been studied quantitatively. Denitrification returns nitrogen to the atmosphere as either nitrous oxide or molecular nitrogen. Atmospheric nitrogen oxides formed from nitrous oxide seem to be involved in the destruction of ozone in the stratosphere. It has been suggested that an increase in the production of nitrous oxide in soils could affect the ozone layer which shields the earth from solar ultraviolet radiation. Locally and regionally, excess nitrate in water increases eutrophication. Similar to phosphorus, nitrate concentrations in ground-water supplies may increase to levels above those recommended as safe by WHO.

The impact of man's activity during the last century has been spectacular in many respects. Through mining, phosphorus has become easily available, enriching food and wastes. Through modern sewerage, a large part of this is conveyed into river courses, changing their ecology. Although, unlike nitrate, phosphorus is practically immobilized in soils, bad farming practices can increase soil erosion, thereby adding more phosphorus to streams. There is the concomitant threat of eutrophication of inland and coastal waters in some regions, plus the fear of depletion of mineable phosphate reserves, critical to world food supplies.

The growth of modern industry increased demands for readily available energy, so far mostly supplied by fossil fuels. The latter contain sulphur, which, on combustion, is released into the atmosphere as sulphur dioxide and then partly deposited as sulphuric acid. The result is an accelerated rate of land denudation and changes in freshwater ecology in regions with hard rocks and numerous lakes. Up to now this problem appears to have been limited to certain regions, but with intensified industry it may become widespread. Sulphur emissions also increase rates of corrosion and are a health hazard in some areas.

Problems such as those mentioned above might be resolved by better knowledge of the biogeochemical cycles of nitrogen, phosphorus, and sulphur. It is difficult to see how best to improve the environment without first establishing fundamental facts: such facts will also serve to offset the interminable speculation frequently passing for knowledge. The summary given in the following sections is based on SCOPE 7 (Svensson and Soderlund 1976).

b. Flow Charts for Nitrogen, Phosphorus, and Sulphur

As a first objective, an attempt has been made to obtain global estimates of the amounts of the three elements stored in various 'reservoirs' or compartments in nature and of the fluxes of these elements between the different compartments. The division of nature into compartments is arbitrary to some extent. The number of compartments chosen for such a model of nature depends both on the geographical scale of the process under consideration and on the state of knowledge of the process. These inventories and flow charts are presented and discussed in the following sub-sections of this report.

In the flow charts for phosphorus and sulphur (Figures 3 and 4), the preindustrial states are represented by estimated figures of fluxes and storages. The effect of present (1970) human activity is then indicated by figures added to the preindustrial ones, the total yielding the present state.

The flow charts can be regarded as crude compartment models. The dynamic behaviour of the models is, however, not discussed. This is a subject for future studies. Some comments on this subject may, nevertheless, be useful. In the past, very simple approaches were often made implying a dynamic response of a compartment to be linear and of the first order, which meant that the flux from the compartment is directly proportional to the storage alone. Under such circumstances, the response is determined by one parameter, the turnover time, which is obtained by dividing the storage of a compartment by the steady flux from it. However, most compartments in nature do not behave so simply. Taking organic matter in podsolic soils as an example, the turnover time is of the order of 100 years whereas the average age, based on carbon-14, is of the order of 1,000 years. From this it is obvious that a major fraction of organic matter added to these soils is converted into carbon dioxide in a few years time, while a small fraction becomes so resistant that it takes many centuries before it is converted to carbon dioxide; this fraction therefore constitutes the major fraction of organic matter in these soils. This is also true of the oceans and the atmosphere, respectively taken as single compartments. The dynamic features of such compartments are properly described by distributions of transit times. The dynamic features must be taken into account for predictions of future states of biogeochemical cycles.

In the construction of a flow chart, balancing of preindustrial fluxes is sometimes resorted to for computing some of the fluxes. This implies that the chart represents means in stationary states, where limited fluctuations are permitted. Flux balancing is, however, questionable for compartments having large turnover times, and fluxes obtained by balancing convey no new information.

Global flow charts integrate the effects of man's activity over the earth's surface. Since there are large regional differences in that activity and the turnover times of the substances in air are often small, the global flow charts do not give a fair picture of the impact. On the other hand, regional cycles are usually impossible to assess on the basis of present-day knowledge. Part of a cycle can, in rare instances, be outlined quantitatively – as will be seen when discussing the sulphur cycle. Such regional cycles will more clearly show the effect of man's activities.

There are important couplings between the cycles of nitrogen, phophorus, and sulphur as well as with other elements, especially carbon. These have, however, not been considered in any detail in the present report and some are examined in a separate report (Kovda 1975). There are close bonds to other SCOPE Mid-term Projects, especially I.1 (Carbon and oxygen cycling), I.4 (Biogeochemical cartography), V (Simulation modelling), and VI (Environmental monitoring).

c. Nitrogen Flow Chart and Comments

The flow chart presented in Figure 2 is more complex than those for phosphorus and sulphur (Figures 3 and 4) in that the form of nitrogen has been specified. On the other hand, the number of boxes has been reduced. It gives only the net fluxes between the pedosphere, hydrosphere, and atmosphere, and the flows represent 1970. In many instances there are flows of the same compound both to and from the same box, i.e., nitrogen added through fixation and lost through denitrification. This is represented by a closed loop. Nitrous oxide (N_2O) is included in the figures for nitrogen (N_2) in the fluxes from the pedosphere and hydrosphere to the atmosphere (denitrification). The internal transformations in soils and waters between organic-N, ammonium-N, nitrite-N, and nitrate-N are not considered in the present chart. It should be noted that the internal circulation of nitrogen is much larger than the fluxes between the three boxes in Figure 2 (Soderlund and Svensson 1976). The global inventory of nitrogen is given in Table 1.

Nitrogen fixation. The rates of terrestrial nitrogen fixation are taken from Burns and Hardy (1975), giving 139 Tg per year. This is considered as a possible lower limit for the biological fixation. To this amount is added the industrial nitrogen fixation (36 Tg in 1970; UN 1975). An additional amount is fixed through combustion and liberated as NO_x (19 Tg). The value for nitrogen fixation in the aquatic environment is estimated, based on data from Gundersen and Hanson (unpublished), to be 15–80 Tg per year for tropical waters. The fixation rate for temperate waters is not known accurately and is assumed to be 25 percent of that in tropical waters. The total fixation is thus set as 30 to 130 Tg per year for the aquatic habitats including sediments.

Denitrification. Gaseous nitrogen and nitrous oxide are formed by nitrate reduction in anaerobic environments, thus being removed from the system. This can be an important negative effect after fertilizer application in agriculture and forestry, but it can be considered positive when it occurs in sewage treatment plants. Little is known about the quantities of nitrogen and nitrous oxide formed on a global scale. Hahn (1974) estimated the annual N_2O production from the ocean to be 20 to 80 Tg. An additional 16 to 69 Tg of N_2O should be released from the terrestrial habitats. The total amount of nitrogen lost from the pedosphere is given as 108 to 160 Tg (Figure 2), assuming that the pedosphere and hydrosphere are in a steady state. The total inputs and outputs from these boxes are balanced by setting the limits for denitrification. N_2O is transported to the stratosphere at a rate

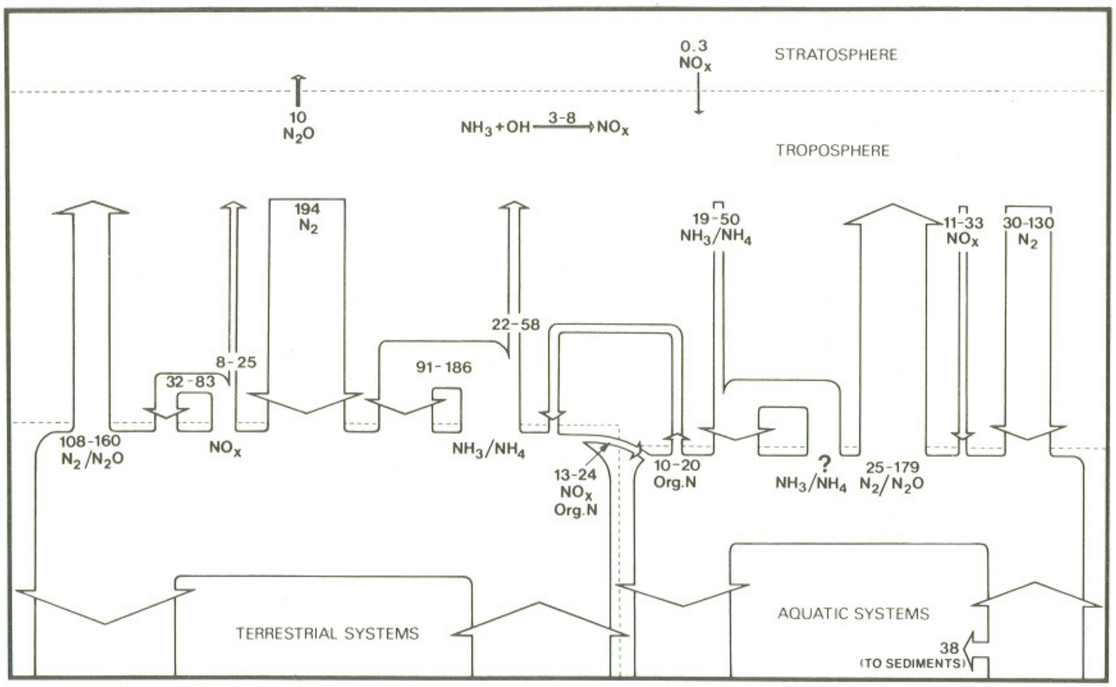

Figure 2 The global nitrogen cycle. The rates are given as Tg N yr^{-1}. The flows of N_2/N_2O are residuals obtained when balancing the terrestrial and aquatic systems (Söderlund and Svensson 1976)

TABLE 1 Global Inventories of Nitrogen in the Terrestrial, Oceanic, and Atmospheric Systems (Tg N) (Schultz, K., Junge, C., Beck. R., and Albright, B. 1970)

System	Reference	Amount
TERRESTRIAL		
Plant biomass	Soderlund and Svensson (1976)	$1.1-1.4 \cdot 10^4$
Animal biomass	Delwiche (1970)	$2 \cdot 10^2$
Litter	Soderlund and Svensson (1976)	$1.9-3.3 \cdot 10^3$
Soil		
Organic matter	Soderlund and Svensson (1976)	$3.0 \cdot 10^5$
Insoluble inorganic	Soderlund and Svensson (1976)	$1.6 \cdot 10^4$
Microorganisms	Soderlund and Svensson (1976)	$5 \cdot 10^2$ [a]
Rocks	Stevenson (1965)	$1.9 \cdot 10^{11}$
Sediments	Stevenson (1965)	$4 \cdot 10^8$
Coal deposits	Donald (1960)	$1.2 \cdot 10^5$
OCEANIC		
Plant biomass	Soderlund and Svensson (1976)	$3.0 \cdot 10^2$
Animal biomass	Delwiche (1970)	$1.7 \cdot 10^2$
Dead organic matter		
Dissolved	Soderlund and Svensson (1976)	$5.3 \cdot 10^5$
Particulate	Soderlund and Svensson (1976)	$0.3-2.4 \cdot 10^4$
N_2 (dissolved)	Delwiche (1970)	$2.2 \cdot 10^7$
N_2O	Soderlund and Svensson (1976)	$2.0 \cdot 10^2$
NO_3^-	Emery et al. (1955)	$5.7 \cdot 10^5$
NO_2^-	Soderlund and Svensson (1976)	$5.0 \cdot 10^2$
NH_4^+	Soderlund and Svensson (1976)	$7.0 \cdot 10^3$
ATMOSPHERIC		
N_2	Robinson and Robbins (1970)	$3.9 \cdot 10^9$
N_2O	Schütz et al. (1970)	$1.3 \cdot 10^3$
NH_3	Soderlund and Svensson (1976)	0.9
NH_4^+	Soderlund and Svensson (1976)	1.8
NO_x	Soderlund and Svensson (1976)	1–4
NO_3^-	Soderlund and Svensson (1976)	0.5
Org. N	Soderlund and Svensson (1976)	1

[a]This amount is inevitably included in the figure for organic nitrogen in the soil.

of 10 Tg per year. This N_2O is converted to N_2 (80 percent) and NOx and there are at present no indications of N_2O accumulation in the stratosphere.

NO_x-production. NO_x (NO and NO_2) is formed during combustion, and this anthropogenic source was estimated by Robinson and Robbins (1970) to be 16 Tg in 1965 (there has probably been an annual increase of 4 percent since), but this value is probably too low. It has also been reported that NO_x is liberated from soils (Kim 1973) and a rough estimate for a possible global production gives 1 to 74 Tg. NO_x wet and dry deposition over oceans (mainly in the form of NO_3^-) is estimated

to be 11 to 33 Tg, and it is assumed that this amount was formed over land. NO_x is further transported from the stratosphere to the troposphere at a rate of 0.3 Tg per year.

Ammonia. The amount of ammonia liberated from the pedosphere is calculated using data for nitrogen as urea in animal faeces. It is estimated that 5 to 10 percent of the urea produced is lost to the atmosphere, but this might, especially in regions with high pH or intensive cattle farming, be much higher. Of the total amounts (26 to 53 Tg), 2 to 6 originates from wild animals, 20 to 35 from domestic animals and man, and an additional 4 to 12 from the burning of coal. The liberation of ammonia is highly variable on a regional scale as is the adsorption of ammonia from the atmosphere by plants and soil. Liberation and adsorption of ammonia are mainly dependent on soil pH; this is indicated by maps of ammonia in rainfall over the USA (Junge 1958). The ammonia/ammonium in rainfall is estimated at 20 to 80 Tg, and this gives a total net flux from the pedosphere to the atmosphere of 15 to 40 Tg per year. Ammonia deposition over the oceans is estimated at 15 to 60 Tg, and, in order to balance this, the ammonium flux to the atmosphere from the pedosphere is set at 113 to 244 Tg.

River runoff. The total amount of nitrogen transported from the pedosphere to the hydrosphere by river runoff is calculated from data given by Ahl and Oden (1972) as 13 to 24 Tg. Better data for river runoff for nitrogen and phosphorus will be available as a result of the UNESCO inventory 'world register of rivers discharging into the oceans'.

d. Implications of Man's Activity for the Nitrogen Cycle

Global impact. The industrial fixation of atmospheric nitrogen is substantial. A part of the nitrogen thus added to soil will, through denitrification, be lost to the atmosphere. From the data given above, 15 to 40 percent of this nitrogen will be in the form of nitrous oxide (N_2O). A source of major concern in this context is the possible increase in stratospheric N_2O, which will cause a decrease in atmospheric ozone. The calculated effect is that a 1 percent increase in nitrous oxide causes a 0.2 percent decrease in ozone (Crutzen 1974). Man has also increased the biological nitrogen fixation through the cultivation of leguminous crops. The impact of increased biological nitrogen fixation is not known.

Regional impacts. In regions with intensive agriculture, heavy use of commercial fertilizers may lead to an increased leaching of nitrogen, especially nitrate, from the soil to water courses, and this will have regional and local effects.

Fixation of atmospheric nitrogen takes place during combustion processes, releasing mainly NO_x into the atmosphere. Nitric acid is then formed and deposited on the ground. In industrially developed regions this adds to the acidification problem of soils and freshwater systems unless denitrification occurs. This acidification may be partly counteracted by fertiliser application of fixed nitrogen as nitrate, since an equivalent amount of alkalinity results from denitrification and the escape of nitrogen or nitrous oxide

NO_x is toxic in high concentrations and is the main component of photochemical processes causing smog.

Local impacts. Nitrogen compounds leached from soils can contribute to eutrophication in fresh and brackish water systems. Changes in agricultural and silvicultural practices, such as intensified tilling and clear-cutting of forests, can mobilize nitrates through increased decomposition of organic matter.

Increased nitrate concentrations in ground water and waters used for human consumption can lead to health hazards. The nitrate concentration in crops also rises after heavy fertilization. Nitrate can be converted to nitrite, causing methaemoglobinemia, or to nitrosamine which is carcinogenic, but the scale of these problems needs further study.

e. The Nitrogen Cycle: Trends

The use of nitrogen fertilizers promises to increase. It has been estimated that there will be a 25 percent increase in Sweden over the next ten years (Kumm 1976). An upper limit for global use of nitrogen fertilizers was estimated as approximately 300 Tg per year. It is, however, possible that increasing energy prices will put constraints on the upper possible limit for nitrogen fertilizers. It is also possible that biological nitrogen fixation will increase considerably in the future as a result of the use of efficient non-symbiotic associations, the increased use of symbiotic associations, and the possibilities for genetical transfer of nitrogen-fixing ability to non-fixing plant species. Increased biological nitrogen fixation on a local scale could have the same impact as commercial fertilizers.

A substantial increase in the use of high altitude aeroplanes (for example, supersonic airliners) causing additional production of NO_x in the atmosphere would have an effect on the protective ozone layer.

f. Phosphorus: Flow Chart and Comments

The main features of the global biogeochemical cycle of phosphorus are illustrated in Figure 3 (based on Pierrou 1976). Some of the fluxes are labelled for easy reference. Amounts in the compartments are set within frames.

Atmosphere. The amount of atmospheric phosphorus is given as much less than 3 Tg.

Ocean surface water. This is the surface layer of the oceans down to about 100 meters depth, which is the approximate depth of the thermocline. This compartment contains the so-called euphotic zone. The average phosphorus concentration given is probably correct within ±0.1 Tg.

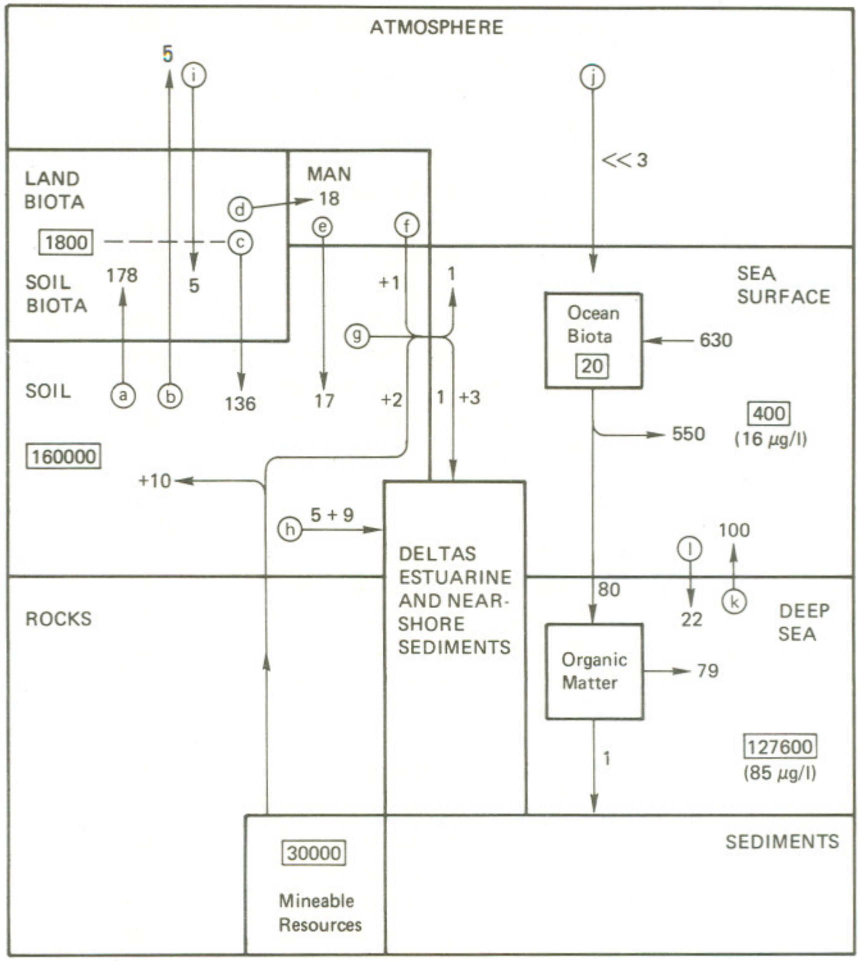

Figure 3 Preliminary global phosphorus flow chart. The units are Tg (million metric tons) per year (based on Pierrou 1976)

Deep sea. This is the remainder of the oceans with a volume of about 60 times that of the surface water compartment. The average phosphorus concentration is probably correct within ±13 Tg. The fluxes *k* and *l* are caused by the rate of exchange of water between the two compartments, using a turnover time for the deep sea compartment of 1,200 years, consistent with the carbon-14 distribution in the oceans. The water exchange causes a net transport of dissolved phosphorus from the deep sea compartment to the surface water compartment, largely balanced by the phosphorus in sinking particulate matter. This particulate phosphorus is released by decomposition in the deep sea compartment. The same internal cycle in the oceans is also found for carbon, nitrogen, calcium, and silicon. For sulphur it is masked by the high concentration of sulphate in sea-water.

Soil. This is taken to represent surface deposits on land down to about 1 meter depth, a possible average depth of the root zone. The storage is computed from an average phosphorus abundance of 0.11 percent by weight and a bulk density of 1 metric ton per cubic meter. A great deal of the storage is not readily available to plants although species differ considerably in their ability to take up phosphorus from soils. The storage is probably correct within ±50 percent.

Five Tg are transferred from soil to the atmosphere in dust. The figure is rather uncertain. Little of this is assumed to be carried into the sea and added to sea spray to form flux *j*. Some leaching of phosphorus from soils as dissolved phosphate seems to take place, ending up in the sea (flux *g*). This amount is fairly small. It corresponds to a mean river-water concentration of 30 micrograms per liter. A far greater loss of phosphorus from soils takes place through erosion (flux *h*). The figure is derived from a 'natural' denudation rate of 1 meter per 35,000 years, estimated from sedimentation rates in inland basins. Since the present denudation rate is about 3 times the natural, the addition of 8 Tg corresponds to a human effect. Most of the particulate phosphorus will end up in deltas, estuaries, and near-shore sediments, for which a separate compartment is shown. Phosphate mining at present amounts to 13 Tg per year of which 11 Tg is applied to agricultural soils. The rest is used industrially and domestically, mostly ending up in rivers. A special compartment, mineable resources, is given a storage of 30,000 Tg, using those phosphate ores containing 5 percent phosphorus or more. If a lower percentage is used, resources increase considerably.

Land and soil biota. This consists of phosphorus in vegetation and animals. The storage is from Woodwell and Pecan (1973). The reliability of this estimate is unknown. It is based on a plant biomass of 1.8×10^6 Tg (dry weight) and a phosphorus content of 0.1 percent.

As to the fluxes, the plant uptake, *a*, is taken from Bazilevich (1974), and is the part of the decay that is handled by man. A greater part is brought back to soil (flux *e*) while *f* is addition of phosphorus from human excreta to rivers. The amount is taken to represent a human effect, since waste release into fresh water is a departure from older practices.

g. Phosphorus: Implications of Man's Activity

Global. The internal circulation and the large storage of phosphorus in the sea can absorb fairly large additions without any noticeable effect.

Regional. On regional scales, the effects of man on the phosphorus cycle would be limited to aquatic systems on land and along coasts. Of particular interest are regions with an abundance of freshwater lakes having considerable water supply and recreational value. It is well known that eutrophication can occur by the addition of phosphorus from municipal sewage and from agricultural land. This is, however, mostly a local problem.

In coastal areas eutrophication may occur by addition of phosphorus to bays where exchange of water with the open sea is impeded. The effect also depends on freshwater inflows to bays causing estuarine circulation patterns which tend to accumulate phosphorus naturally. Such bays or even inland seas, such as the Baltic, have a tendency to develop anoxic conditions in deeper water because of stable density stratification and oxygen depletion by sinking particulate organic matter. In such cases even moderate additions of phosphorus from land can increase the anoxic conditions.

h. Phosphorus: Future Trends

The amounts of mineable phosphate reserves are dependent on the grade of the ore and will be reflected in the price the consumers are willing to pay for the phosphorus. Estimates of the world-wide reserves must take this into account. It is possible to estimate probable upper limits for phosphate fertilizer use, attainable only under the extreme conditions of scarcity of food and low fertilizer production costs relative to food prices. Such estimates do not represent forecasts. Under the conditions stated, the rate of phosphate fertilizer addition on a global scale could reach 50 Tg per year, or four times the present rate. If marginal pasture land is also taken into account an additional 20 Tg can be added.

A rate of 50 Tg per year is, of course, considerable in relation to present uptake by plants. It would of necessity increase the uptake somewhat, although a major part would add to the soil storage. Erosion rates would probably increase so that losses of phosphorus would also increase.

Regional effects of such an increase in fertilizer use would be inevitable.

i. Sulphur: Flow Chart and Comments

In recent decades many attempts have been made to describe the circulation of sulphur in nature in a consistent way, particularly with regard to the flux through the atmosphere. The circulation and transformation of sulphur in nature is still inadequately known and much uncertainty exists with regard to the mechanism and importance of processes involved.

It should be stressed that man-made sulphur emissions are confined to rather limited regions of the earth's surface. Since the residence time in the atmosphere of most of this sulphur is only a few days, the impact on the environment of this pollution constitutes a regional problem (scales of a few thousand kilometers). For most impact studies, regional budgets would therefore be more relevant than global budgets. As an example, a budget for the atmosphere over Northwest Europe is presented in Table 2.

On the other hand, the potential use of global budgets is to assess man's possible contribution to the global concentration of aerosols which may be of importance for the global radiation balance. Two examples of a global sulphur budget are presented (Figures 4 and 5). The first is based on an estimate of a preindustrial balance between sources and sinks for the soil, providing some indirect evidence of

TABLE 2 Sulphur Budget for NW Europe (Tg S/yr) (based on Rodhe 1976)

	Pollution Sulphur	Non-pollution Sulphur	Total
Emissions	13	?	13 + ?
Deposition			
By precipitation	4.1	0.5	4.6
By direct uptake	2.9–5.9	0.2–0.3	3.1–6.2
Total	7.0–10.0	0.7–0.8	7.7–10.8
Net export of pollution sulphur	3.0–6.0		
Net export as percentage of emissions	23–46		

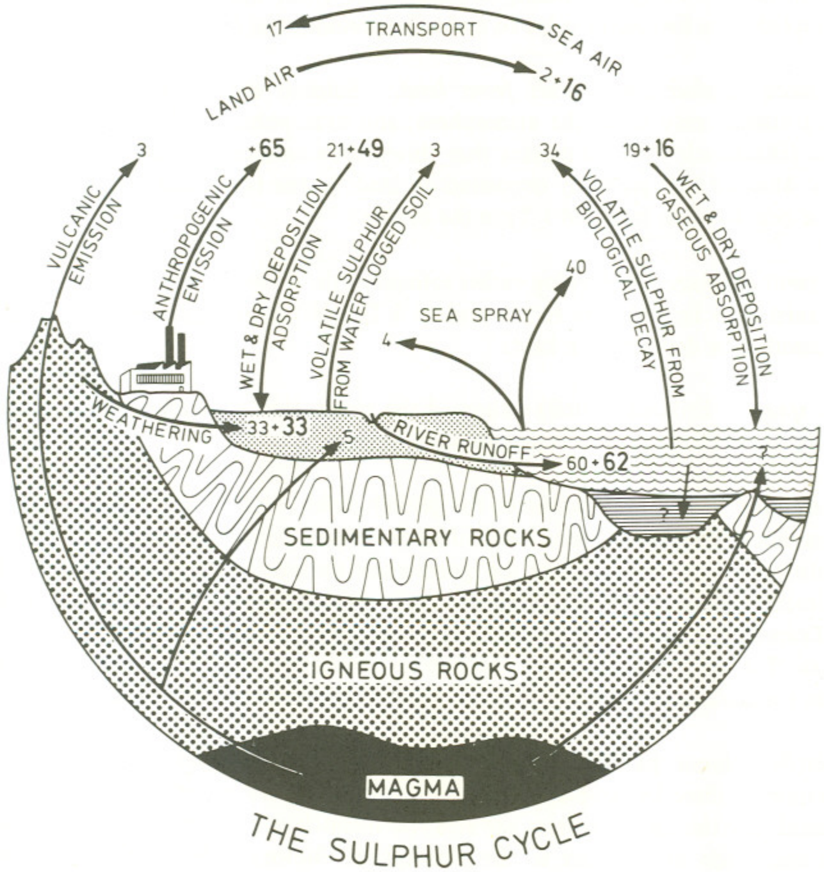

Figure 4 The first global sulphur cycle, based on a preindustrial balance of the soil compartment. Fluxes are given in Tg (millions of tonnes) of sulphur per year. The man-made parts of the fluxes are indicated by plus signs (Hallberg 1976)

the quantities involved in the atmospheric budget. The second budget is based directly on atmospheric chemistry information, in particular rainwater analyses.

j. Sulphur: First Global Budget

This global sulphur budget (Figure 4) is based on the assumption that there was a preindustrial balance between sources and sinks for the soil (Hallberg 1976). The flux of non-pollutant sulphur through the atmosphere is estimated to balance the estimated preindustrial river runoff.

River runoff. Eriksson (1960) estimated the total annual river runoff of sulphur at the turn of the century to be 75 Tg per year. According to Robinson and Robbins (1968) man-made sulphur emissions increased by 12 Tg from 1850 to 1900. Hence, 15 Tg (including contributions from mining and agriculture) is deducted from Eriksson's value to make the preindustrial runoff 60 Tg.

Reduced sulphur compounds from land. Sulphur derived from decomposing plant tissues may enter the atmosphere, and extrapolation of available emission data (Hitchcock 1976) indicates that this source amounts to only 2 to 5 Tg per year. Most of it is probably deposited on land. In the flow chart 2 Tg are assumed to be deposited on land and 1 Tg in the oceans.

Volcanic sulphur. Following earlier estimates, the contribution to the atmosphere is taken as 3 Tg and that to the soil as 5 Tg. Of the atmospheric part, 2 Tg are assumed to be deposited on land.

Sea spray. Eriksson (1960) estimated the production of sea-spray sulphur to be 44 Tg of which 10 percent is precipitated on land.

Weathering. The best estimates for preindustrial conditions are those based on denudation rates (Eriksson 1960, Judson 1968). However, weathering of the continental crust is not equal for igneous and sedimentary rocks because of their different resistance to weathering and their different areal distribution. According to Conway (1943) only 0.2 of the weathered continental crust comes from igneous rocks. The sulphur content of the average weathered rock is 0.33 percent which gives a mean annual value of 33 Tg for preindustrial weathering of sulphur.

Volatile reduced sulphur compounds from marshes, estuaries, and ocean. The emission of dimethyl sulphide from the ocean to the atmosphere has recently been studied but the measurements are still too inconclusive to warrant an estimate of the magnitude of this flux to the atmosphere. Biological decay under anaerobic conditions results in production of hydrogen sulphide whenever sulphate is present. Such environments, created by sulphate-reducing bacteria, are very common in tidal marshes and estuarine areas. They are also common in oceanic sediments except in the uppermost part which is usually oxidized. Because of the very short residence time (a few hours) for hydrogen sulphide in oxygenated waters it is unlikely that it escapes from deep water sediments to the atmosphere. The most probable process is release of hydrogen sulphide or other volatile reduced sulphur compounds from mud cracks in the intertidal zone. Measurements of sulphate removed from tidal waters flushing a marsh on the North Shore of Long Island, New York (Woodwell 1976) showed that if only a few percent of this is released in the form of volatile sulphur compounds into the atmosphere, the amounts would be sufficient to balance the preindustrial soil compartment. Thus the total flux of volatile reduced sulphur compounds into the atmosphere from coastal areas of the oceans is estimated in the following way. The preindustrial balance of the soil requires an atmospheric addition of 25 Tg. Four of these come from sea spray and another 4 from volcanic and biological sources on land. The remaining 17 Tg are assumed to originate from the previously discussed source. Assuming that 50 percent of the coastal emission is deposited on land, a flux of reduced sulphur from the coastal areas of the oceans is estimated to be 34 Tg.

Deposition on land and ocean. These figures (21 on land and 19 on the ocean) are obtained indirectly in order to balance the atmospheric compartment. It may be assumed that roughly 50 percent of the deposition is by precipitation and 50 percent by dry deposition.

Man-made contributions. Man has influenced the magnitude of several of the fluxes (Figure 4). These numbers are indicated in the diagram by a plus sign.

Fossil fuel combustion. According to Friend (1973), the annual sulphur emission to the atmosphere around 1965 was 65 Tg: 75 percent of this is assumed to be deposited on land.

Impact on weathering. Berner (1971) concluded that sulphur from rock weathering constitutes 35 percent of the total dissoved sulphur in the world average of river water. Based on Livingstone's data (1963), this corresponds to 42 Tg. Using 0.33 percent for the sulphur concentration of the average weathered rock and Judson's (1968) figure for world-wide river gauging, we obtain a figure of 105 Tg. The true value may lie between these and a figure of 66 Tg is chosen. Compared to the preindustrial figure this means that man has doubled the weathering rate.

Impact on sulphate reduction in marshlands. The limiting source for bacterial production of hydrogen sulphide is the supply of decomposable organic matter. In many coastal areas man has increased this supply and hence affected the production of hydrogen sulphide. No data exist.

Present river runoff. Livingstone's data (1963) for total annual runoff of sulphur is 122 Tg. As some of the data he used are from the end of last century or from the beginning of the present, the present runoff may be expected to be higher.

However, there is no need to balance the present state of the soil compartment. The soil storage may be changing at present.

Storages. In the soils of humid areas practically all sulphur stored is bound in organic matter. The semi-arid or arid areas soils and subsoils contain from 1 to 3 percent to as much as 15 to 60 percent of inorganic sulphates. The human impact on the cycle is fairly large when comparing preindustrial and present fluxes. Yet it is probably fairly small with respect to storages, except for the atmosphere.

k. Sulphur: Second Global Budget

The second budget (Figure 5) is based primarily on rainwater analysis (Granat 1976). A critical examination of available data especially in the light of recent quantitative knowledge about long distance transport of anthropogenic emissions, gives a rather different picture compared to what has hitherto been accepted (Friend 1973). A key question is, as before, the magnitude of the natural production of reduced sulphur compounds, as this is considered to be of particular relevance for the formation of aerosols in a size range that may interfere with visible radiation. Sea spray formation and suspension of soil dust are also considered in the budget scheme inasmuch as a small fraction of this material may be found in the size range below about 0.8 μm.

It must be noted that present information about processes and magnitude of fluxes in the natural sulphur cycle is insufficient for even approximate estimates. The uncertainty in the estimates is therefore probably not less than a factor 2 at the very best, except for that of man-made emissions.

Deposition with precipitation (wet deposition) is estimated from rainwater analysis in areas not affected by long distance transport of anthropogenic emissions as well as from an estimate of the possible natural contribution in Europe. It is estimated to be 18 Tg sulphur per year for land areas and 11 Tg sulphur per year for the ocean. These are considerably lower values than previous estimates. They do not include that portion of the sea spray which is in the form of particles larger than about 1 μm and which is removed by precipitation. In addition there is some 30 Tg sulphur per year emanating from man-made emissions deposited by precipitation.

Estimation of dry deposition of sulphur compounds from natural sources involves consideration of both reaction rates and pathways in the oxidation of H_2S, DMS, and other reduced sulphur compounds. A value of 0.1s $g\ S\ m^{-2}\ yr^{-1}$ is adopted in this budget, based on the limited and to some extent contradictory information available. If dry and wet deposition over land and sea is compared with the contributions from volcanoes (3 Tg S), decay processes on land (5), and sulphur from sea spray in submicron particles (3), there is a deficit of some 27 Tg sulphur per year. This may be explained in two ways. The wet deposition may be overestimated due either to contamination during sampling or to unrepresentative sampling points. Alternatively, the production rates of gaseous sulphur compounds may be underestimated. The second alternative is considered

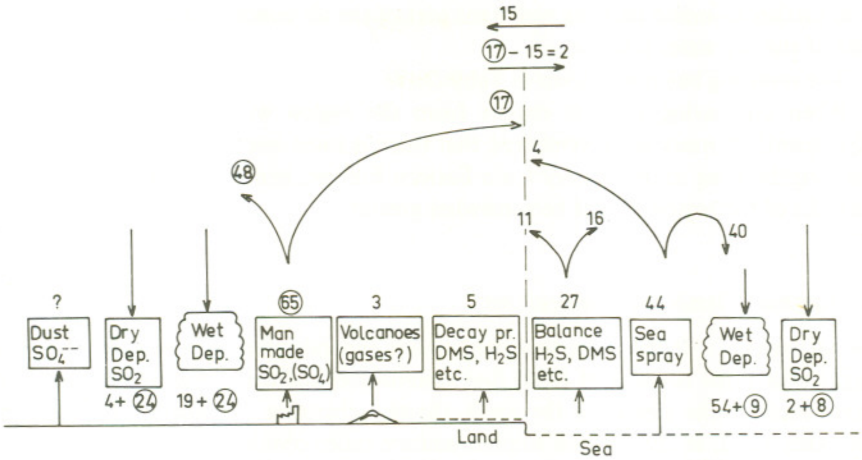

Figure 5 The second global atmospheric sulphur cycle, showing major source and sink mechanisms over land and sea. The fluxes emanating from anthropogenic emissions are encircled. The 'balance' flux, i.e., emission of reduced sulphur compounds that cannot be estimated directly may also take place over land areas (Granat, Rodhe, and Hallberg 1976)

the most likely. Possible source areas are tidal flats or other salt shallow waters and some additional production on land.

According to investigations over Europe the global man-made emission of 65 Tg sulphur per year can be removed equally by dry and wet deposition processes. About 0.70 of this will be deposited over land, the remainder over the oceans.

The tropospheric storage can be calculated from the production rate of submicron particles if the average residence time is known. A value of 5 days is adopted, giving a content of about 0.3 Tg sulphur in the troposphere. This can be compared with the storage of S in submicron particles due to man-made emissions which is estimated to 0.2 Tg sulphur.

l. A Regional Sulphur Budget for Northwest Europe

The problems and findings attached to estimating a budget for the atmosphere of a region are demonstrated by a calculation for Northwest Europe (Rodhe 1976).

The region studied is bounded by 65°N, 45°N, 10°W, and 250°E with an area of 4.62 million square kilometers. The following data have been used for years around 1973:

Non-pollution sulphur in precipitation, 0.2 mg per liter (Nordø 1976)
Sulphur deposition in precipitation from Sweden's Case Study (Bolin 1971)
Concentration of SO_2 sulphur in surface air, (LRTAP) data)
Deposition velocity of SO_2, 0.5 to 1 centimeter per second
Man-made sulphur emissions, 13 Tg per year

It is further assumed that the pollutant part of the air concentrations is the same as that of the rainwater sulphur.

The resulting balance is given in Table 2.

When comparing the net export from the region with the emission (about 30 percent), it must be remembered that there is some import into the region from the neighbouring areas, mainly from Eastern Europe, and that therefore the gross flux out of the region should be somewhat greater.

m. Sulphur: Trends and Implications

Global impact. It has been suggested that a general increase in sulphate particles might take place because of fossil fuel combustion and that these form a haze that might increase the albedo of the earth, thereby changing its radiation balance. On the other hand, in the data on sulphur/sodium ratios obtained from dated ice cores in Greenland (Koide and Goldberg 1971) there is no observational evidence of a change in this ratio paralleling the industrial development. There are few other reliable data on the subject.

Regional impacts. The major impact of fossil sulphur is on the regional scale. It is converted into sulphuric acid, which on deposition, dissolves equivalent amounts of any basic minerals present in the soils. The effect is then an increased rate of leaching from soils. When the soil cover is thin or consists of bogs, the deposited acid will accumulate in freshwater systems, lowering the pH to such an extent that a drastic change in biota takes place. This is at present the case in parts of Scandinavia and in some areas in North America. It should however, be pointed out that acid deposition on land is not due to fossil sulphur alone. Reduced sulphur coming from ocean areas will also be deposited on land as sulphuric acid and thus also contribute to the leaching of soils.

Man's addition of fossil sulphur has increased leaching of soils considerably in some humid regions. To what extent this leaching is decreasing the growth rate of coniferous forests is a subject under current discussion and so far there is no conclusive evidence. Because of the appreciable storage of nutrients in soils it may take a considerable time before the effects of leaching can be discovered. There is also the possibility that the acid deposition might affect nitrogen fixation by microorganisms in the soil thereby reducing soil productivity. Nitrification is inhibited by acidity, and this process is known to be sensitive to external changes. These are examples of a coupling between cycles of different elements. In contrast to the processes in humid regions, in arid areas sulphates are deposited in the process of soil salinization.

n. Further Research on Nitrogen, Phosphorus, and Sulphur Cycles

It is obvious that there are serious gaps in knowledge of the biogeochemical cycles of nitrogen, phosphorus, and sulphur. Inventories are needed, in particular for nitrogen, phosphorus, and sulphur in soils, since soils constitute a considerable storage. Such inventories will most likely reveal geographic patterns whose recognition will aid understanding of biogeochemical processes and their dependence on the physical and chemical environment (see Section C3 below). It is desirable to investigate the dynamics of major compartments, and especially the dynamics of soils in order to permit forecasts of effects of human activities. More should be known about the rapid turnover within each compartment and the transfer rates between compartments.

In the nitrogen and sulphur cycles, the atmosphere is a compartment for which knowledge is least complete. Phosphorus is a minor component of the atmosphere, but concentrations and origins of various phosphorus compounds are unknown. Patterns of deposition from the atmosphere are unknown over large areas. Extensive data collection on a routine basis will be required. Better techniques are needed for measuring air and precipitation concentrations of almost all compounds discussed in this section, particularly for measurement of background concentration values such as those found outside cities and industrial regions and in the free atmosphere.

More specific research prolems can be identified for each of the three elements.

Nitrogen. Although denitrification is an important process in the cycling of nitrogen, its rates in nature are poorly known. The influence of factors such as nitrate concentration, soil water content, and oxygen concentration on reaction rates and the N_2O/N_2 ratio of the gaseous end-product should be investigated in terrestrial and aquatic habitats. Geographical variations should be determined. It is important to verfify whether the soil can act as a sink for N_2O, and if so whether that leads to a further reduction to nitrogen gas or assimilation of nitrogen by the soil microorganisms. A possible tropospheric sink for N_2O should also be explored. Deepened knowledge of the atmospheric N_2O cycle would enhance the capacity to forecast future N_2O concentration levels as they may influence the ozone layer.

Little is known about the rates of biological nitrogen fixation in non-tropical waters. The possible environmental effects of increased biological nitrogen fixation should be examined. The possibility of genetic transfer of nitrogen fixing ability to presently non-fixing species and the resultant effect on the local and regional nitrogen cycles should be assessed. With a view to diminishing use of nitrogen fertilizers, several aspects of biological nitrogen fixation should be investigated in the hope of finding suitable species and efficient systems for use with present or new management techniques. Although the possible effect of heavy metals, pesticides, and other pollutants on nitrogen fixation has already been investigated in some detail, a complete overview on the effect on the nitrogen cycle is needed.

Methods should be sought to minimize any adverse effects, such as leaching of nitrate from soils, or decrease in biological nitrogen fixation, from management practices, including the use of nitrification inhibitors. This will become more important as the prices of nitrogen fertilizers increase.

Because nitrogen flows are variable on a regional scale, especially with regard to ammonium, local and regional nitrogen budgets of $NO_x(NO_3^-)$. and NH_3 (NH_3^+)

are needed to better elucidate man's impact. These would assist in evaluating the effect of changes in land use, including urbanization, on the nitrogen cycle.

To the degree that NOx is produced in gaseous form from soils as well as from combustion processes, it would be an important factor in accounting for the observed NOx concentrations in the atmosphere and should be investigated. Further measurements on background levels of NOx, and of NH_3, in the atmosphere are desirable.

Phosphorus. The concentrations of phosphorus and the origin of phosphorus compounds in the atmosphere are unknown and should be investigated. Understanding the formation of ocean sediments, and information about aeolian transport of phosphorus-laden dust from land to ocean would be valuable.

Much information is available concerning the use of fertilizers. However, to be able to minimize the use of phosphorus fertilizers, the efficiency of various forms should be evaluated.

Much of the phosphorus loading of waters affected by eutrophication originates from industrial and household consumption rather than from fertilizers. Means by which such uses of phosphorus could be reduced should be investigated. Studies on the use of phosphorus from sewage sludge should be continued. The effect of various forms of sewage treatment on the distribution of phosphorus, as well as nitrogen and sulphur, should be investigated.

Sulphur. In order to be able to estimate the total inventory and ground deposition of atmospheric sulphur, more detailed measurements are needed on the concentration of SO_2 and sulphate aerosols (particularly in surface air in remote areas over the continents), as well as in higher layers of the atmosphere (particularly in the 5 to 10 kilometer region) at a few different latitudes. Measurements of sulphate concentration in cloud droplets on a world scale and of wet deposition of sulphate in remote areas, are recommended, provided that the problem of contamination can be handled properly. In general, the basic chemistry of sulphur compounds in an atmospheric environment also needs to be understood better.

An important part of the sulphur cycle is the production of reduced, volatile sulphur compounds (hydrogen sulphide and dimethyl sulphides), but the amounts thus released from decomposing organic matter are not known. The most important areas for this production may be interidal flats. In situ measurements from such areas are urgently needed. Measurements are recommended for air and precipitation concentrations of the various sulphur compounds in coastal areas with tidal flats and at different distances from the coast, and where the anthropogenic contribution is either small or known.

Better data on sulphur in river runoff are needed, especially as sulphur is not included in the UNESCO inventory on world river discharges into the oceans.

It is possible that the present sulphur deposition from the atmosphere in industrial areas with intensive agriculture is sustaining the crop yields, and that a reduction in atmospheric sulphur fall-out would affect the production from some crop lands. This should be investigated by making local sulphur budgets. The possibility of foliar SO_2 absorption should be taken into account in this context.

The effect of acid precipitation on primary production should be assessed, both on a functional level and at the ecosystem level. The possibilities for drastic changes in, for example, leaf/needle pH and the resultant effect on photosynthesis and phyllosphere organisms deserve examination.

3. Carbon

A major global concern is the effect of human activities on the biogeochemical cycle of carbon. The release of carbon from fossil fuels and changes in the terrestrial carbon pool caused by agricultural and forestry practices are large enough to be significant in natural global processes. A schematic representation of the global carbon cycle is given in Figure 6. Ever since the Industrial Revolution there have been increasing anthropogenic CO_2 emissions to the atmosphere. These releases reached about 2,000 million tonnes per year in 1900 and about 18,000 million tonnes in 1974 (Keeling 1973, Rotty 1975) (Figure 7).

There are three principal forms of carbon in the atmosphere (carbon monoxide, carbon dioxide, and methane). During the decade 1959 to 1969 atmospheric carbon dioxide steadily increased by a total of 6.8 parts per million (ppm). With an assumed preindustrial concentration of 290 ppm, the increase is approximately 50 percent of the total estimated industrial release of carbon dioxide to the atmosphere (Bolin and Bischof 1970, Ekdahl and Keeling 1973, Woodwell and Pecan 1973, Bolin 1975b).

Methane in the atmosphere is of recent biological origin. It probably reacts with OH-radicals proceeding through a chain of reactions which includes carbon monoxide and ends with carbon dioxide. Therefore, a major portion of the carbon monoxide in the atmosphere would also be of recent biological origin.

Estimates of oceanic carbon pools vary by a factor of three for living matter and a factor of six for dead organic matter. Estimates for terrestrial carbon, particularly dead organic matter, are less certain. They range from 700 to 7,000 units. The terrestrial pool is of special interest because of the large immediate effects human activities can have on it (Hutchinson 1954, Reiners 1973, Whittaker and Likens 1973).

Estimates of exchanges between the various carbon pools in the global system, especially those related to biological processes, are uncertain. Exchanges within the ocean can be estimated using radiocarbon measurements. Estimates of the rate at which oceans can remove carbon released to the atmosphere by the burning of fossil fuels account for only about 50 percent of the amount released. This could mean that the carbon is being assimilated by the terrestrial pool, but it seems unlikely.

The movement of carbon within the oceans has a prominent role in determining the atmospheric concentration. An important part of the oceanic carbon cycle is the assimilation of carbon into living matter in the surface waters. This, in turn, is controlled by the amount of nutrients, such as phosphorus, available in those waters. Carbon and nutrients are typically depleted in surface waters and relatively abundant in deeper waters because they are incorporated in organic matter which, as waste material or dead organisms, sinks to the deep waters where it is released by

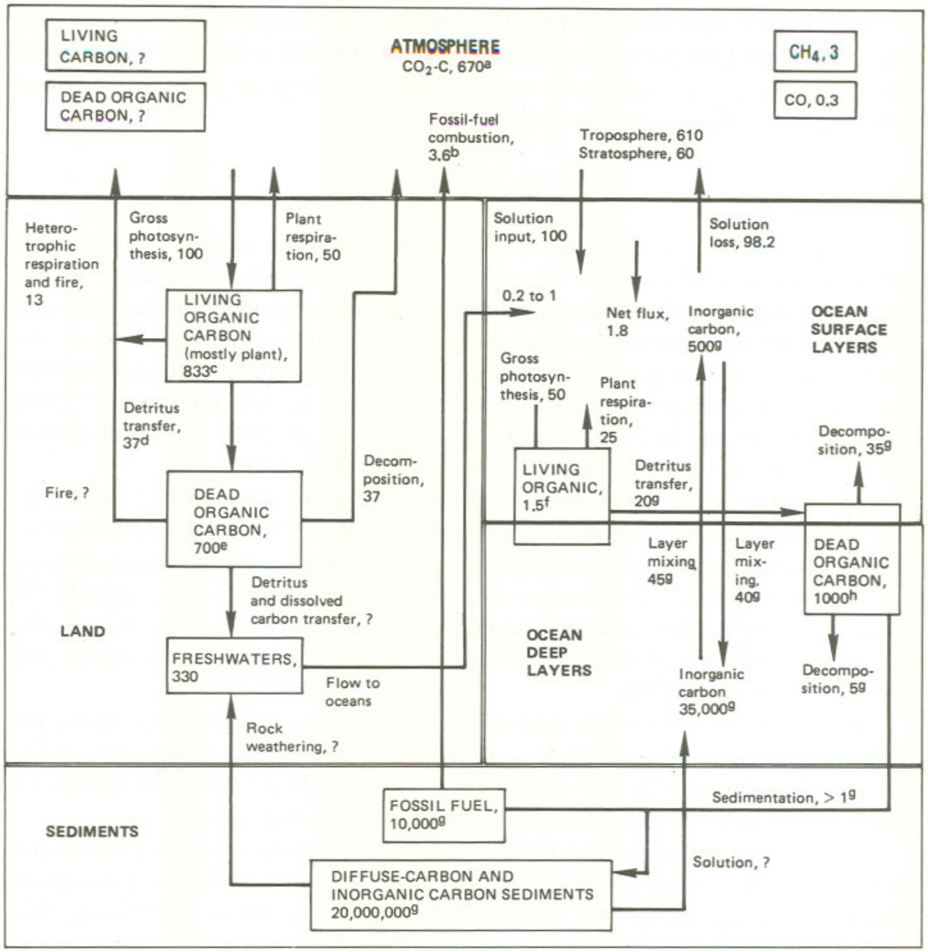

Figure 6 Diagrammatic model of the global carbon cycle. Estimates are given below. Question marks indicate that no estimates are available. Figures are all in billions of metric tons of carbon and are derived from estimates of Brookhaven Symposium participants unless otherwise noted. The following are alternative estimates; (a) Other estimates are 683 (SCEP, Ref. 1, page 161) and 700 x 10^9 tonnes (Bolin), (b) SCEP, Ref. 1, page 304, (c) Bolin estimates 450 x 10^9 tonnes, (d) Bolin estimates 25 x 10^9 tonnes, (e) Bolin, based on Delviche's nitrogen estimate and a carbon/nitrogen ratio of 12, an alternative estimate is 9,000 x 10^9 tonnes, (f) Bolin estimates 10 x 10^9 tonnes, (g) Bolin, (h) Bolin estimates 3,000 x 10^9 tonnes (modified from Remers 1973b)

decomposition. There is, therefore, a danger that interference with the biological processes in the surface waters of the oceans could have a profound effect on the atmospheric concentration of carbon dioxide.

In summary, the world biogeochemical carbon cycle is understood qualitatively, the various reservoirs and pathways being indicated in Figure 6. A number of

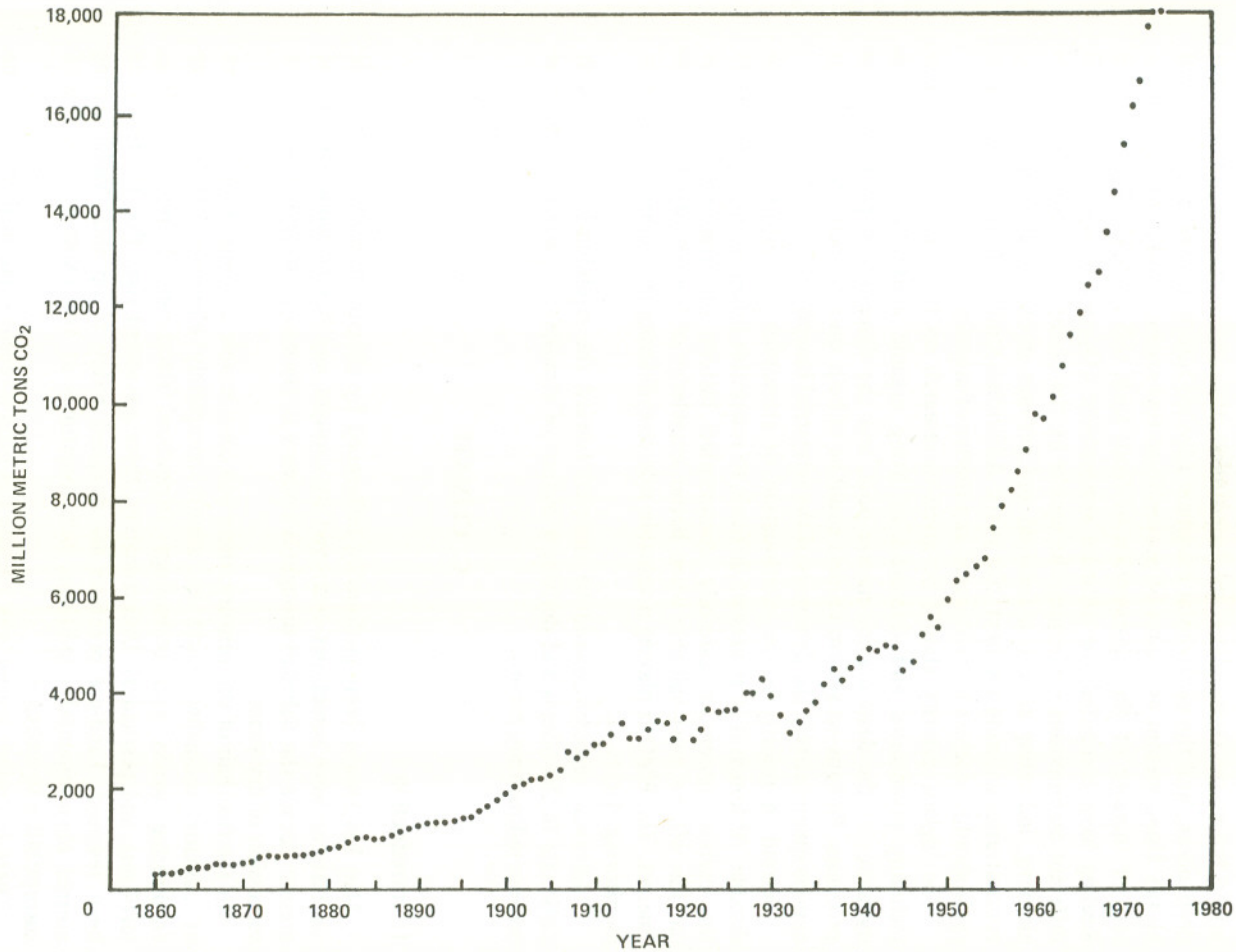

Figure 7 Annual production of CO_2 from fossil fuels and cement (Keeling 1860–1959, Rotty 1960–1974)

quantitative models have been proposed which, although still rather crude, indicate major increases in the atmospheric CO_2 concentrations during the next 200 years. In the model of Bacastow and Keeling (1973), for example, the world is divided into 6 boxes: the stratosphere, the troposphere, the ocean surface mixed layer, the deep ocean, and the continental biosphere (divided into long-lived and short-lived biota). Using present estimates of proven fossil fuel reserves, and assuming that the rate of increase of the consumption of fossil fuels will diminish, Bacastow and Keeling have computed the ultimate atmospheric CO_2 concentrations for several different assumptions concerning the uptake by the oceans. The results are rather alarming, indicating at least a fourfold and perhaps an eightfold increase in CO_2 concentrations during the next 200 years. Additional studies of the global carbon cycle should therefore be encouraged as a matter of urgency.

The highest priority should be given to research on the terrestrial biosphere including inventories and dynamics of living organic matter, inventories and dynamics of the dead organic matter pool, and the dynamics of photosynthetic processes. Perhaps ecosystem models could be of help, once properly developed, to express quantitatively the dynamics of the terrestrial biosphere.

Second in priority is the continuation of atmospheric monitoring of carbon dioxide. Although it is at present difficult to relate this information to the rest of the carbon system, a carefully documented history of atmospheric carbon dioxide will be most valuable when better knowledge of the terrestrial biosphere emerges. The WMO is playing a valuable role co-ordinating the global atmospheric monitoring efforts.

Additional research should be directed toward the equilibration of calcium carbonate in the oceans and deriving a history of atmospheric carbon by using the oceanic sedimentary record.

C. CLIMATE

1. Introduction

Man has always been profoundly influenced by climate. In early times, whole civilizations were sometimes destroyed by drought and famine while even in the present decade the Sahelian drought is evidence of the enormous repercussions of a succession of dry years.

In the first half of this century, there was considerable optimism that the impact of climatic anomalies could be almost completely eliminated through large engineering works and technology (irrigation, flood-control, plant breeding, fertilizers, and pesticides). Unfortunately, there are recent signs that the trend has been reversed. Land-use practices are designed today to optimize yields during normal environmental conditions, but sometimes at the expense of increased susceptibility to extremes.

There is another reason why climate has been a recent topic of discussion. The view has been expressed that man may be inadvertently changing the global climate in irreversible and possibly harmful ways. This line of reasoning is difficult to refute or to accept without a deeper understanding of the nature of climate. What are the causes of climate fluctuations? Are future climates predictable and, if so, in what sense?

It is for these reasons that the study of climate is a priority item over the next several decades.

2. World Climate: Past and Present

a. Types of Climatic Data

Climatic data are obtained from:

(i) Surface weather observing networks, first established in the middle of the nineteenth century, and upper-air networks which began in the 1930's and have recently been extended by satellite observations. The records of a few individual climatological stations date back to the late seventeenth century.

(ii) The written word preserved in diaries, legal and church documents, and so forth. Quite frequently, phenological events such as the blossoming of cherry trees and the breakup of ice on rivers have been recorded. Information of this type can be used to infer some features of the climate over the last 2,000 years or so.

(iii) Palaeoclimatological evidence, such as radiocarbon dating, tree-ring analysis, pollen studies in peat and lake sediments, glaciology, palaeopedology, palaeogeology, and studies of deep sea sediments. Palaeoclimatology provides a focal point for scientists from many different disciplines.

b. Some Properties of Climatic Data

The distribution of weather-observing stations is so uneven that there is difficulty in determining hemispheric or sometimes even regional climatic trends. This problem is heightened by the fact that during the last 50 years many stations were established at airports, where increasing urbanization has since taken place. Land-use changes often have a larger effect on local climate than does a global trend.

Meteorological observations, even at 'ideal' sites, contain three kinds of correlations (Figure 8).

(i) In the first place each observation has a 'memory' and its value is correlated with the previous value. In the case of temperature, for example, there are diurnal and annual cycles as well as long-term upward and downward oscillations in the mean values. An average obtained from a record of given length rarely converges to a 'true' mean as the sampling interval is lengthened. Nevertheless, an average value over a specific 30-year period (e.g., 1941–1970) is often computed by National Meteorological Services in order that spatial comparisons can be made.

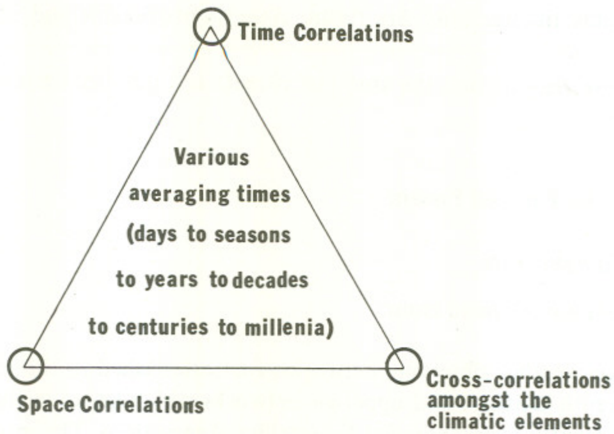

Figure 8 Correlation of meteorological observations

(ii) Meteorological observations contain not only correlations in time but also in space. The weather at a point is similar, to a certain extent, to that in the surrounding region, on time scales of hours, years, and centuries. This coherency is demonstrated by the existence of the Northeast Trades, the Westerlies, and by the global organization of climatic anomalies. For example, a drought in North America often occurs in conjunction with other anomalies around the world. Determination of the extent of these connections is an active area of research (Bjerknes 1962, Namias 1957a, 1957b). There exists the possibility that some of the spatial correlations may be time lagged, permitting predictions of at least some features of the climate from a knowledge of anomalies during the previous season a thousand kilometers or more away.

(iii) The third dimension of the climate matrix indicates the existence of many cross-correlations among the climatic elements. There are correlations between temperature and sunshine, humidity and precipitation, and so forth.

c. The Natural Variability of Climate

For the past 8,000 to 10,000 years, the earth has had a relatively warm interglacial climate. There have been other periods in the last 2 million years, none of which apparently lasted more than 10 to 20 thousand years.

World climate has also fluctuated significantly on a time scale of centuries. There was a warm spell in Northern Europe from about 1000 to 1300 AD followed by a cold period between 1550 and 1700 AD.

In the present century, the temperate and arctic zones of the Northern

Hemisphere were exceptionally warm until about 1940 when cooling began. The spatial organization of the cooling was remarkable, being concentrated in the Spitzbergen/Franz-Joseph Island region (a drop of nearly 6°C in winter temperatures at Franz-Joseph). Meanwhile in New Zealand, the reverse trends were experienced (Salinger and Gunn 1975); the period 1900 to 1935 was the coldest in recorded history while the climate has since become warmer. That this is not an isolated result is indicated by a recent study of Australian climate (Tucker 1975). Although the data base in the Southern Hemisphere was admittedly incomplete, the associated world pressure anomalies were consistent, revealing that (Salinger and Gunn 1975):

(i) when the subtropical anticyclones were farther north than usual, as in the period 1900 to 1935, the weather was warm in the Northern Hemisphere and cool in the Southern;

(ii) when the subtropical anticyclones were farther south than usual, as in the period 1950 to 1970, the reverse temperature regimes prevailed.

This is a good example of spatial coherence on a time scale of decades. Scientists in many disciplines have contributed data on past climates. The task of synthesizing these data is associated especially with the names of Lamb in the UK, Flohn in FRG, and Kutzbach and Mitchell in the USA.

d. Man's Impact on Climate

Man changes local climate in many ways. The surface heat balance is substantially modified whenever a forest is cut, a field is ploughed, snow is removed, or a parking lot is paved. The expression 'urban heat island' is widely used to indicate that temperatures in built-up areas are higher than in the surrounding countryside, but the other climatological elements are also affected. With the growth of the megalopolis, these local anomalies are becoming regional.

Other possible reasons for local climate modification can be cited:

(i) river diversions or control, creating new lakes or changing the salinity and ice-cover of coastal zones;

(ii) the destruction of tropical forests, changing the surface heat balance and roughness, and reducing evaporation (Potter et al. 1975);

(iii) changes in agricultural and forestry practices, such as slash burning, and irrigation affecting the surface heat balance;

(iv) changes in the numbers and/or sizes of condensation nuclei emitted to the atmosphere, affecting cloud formation and dissipation; and

(v) releases of krypton-85, changing the electrical properties of the atmosphere. This 'problem of the future' could affect thunderstorm activity and associated precipitation patterns (Boeck et al. 1975).

There is no evidence to suggest that any of these mechanisms influences the synoptic-scale weather patterns crossing overhead, although the micro- and even the meso-climate may be considerably affected. In contrast, it has been known for 25 years that the Great Lakes (a large heat source in autumn and winter; a small heat sink in spring and summer) influence the movement and development of weather systems in Eastern North America (Danard and McMillan 1974). Thus the possibility exists that some of the factors listed above could ultimately affect the general circulation especially if human population expansion is accompanied by increased urbanization and energy generation. According to Sawyer (1974), an increase of about 50-fold in European or North American heat releases could 'produce a climatic change comparable with the year to year variation which we experience naturally'.

Another possible way of affecting climate is by modifying the atmospheric radiation balance, which might lead to changes in the general circulation. Particulate matter and a few gases, especially CO_2, which absorb and re-emit terrestrial radiation in selected wave-bands are candidate substances. There is also some concern about gases such as chlorofluorocarbons that not only could affect the radiative balance of the atmosphere but also could react chemically in the stratosphere, disturbing the ozone layer (see Section 4(c) below).

Bryson (1974) captured public attention with his hypothesis that the atmospheric cooling in high latitudes of the Northern Hemisphere since 1940 had been caused in part by an increase in particulate matter released by man. Bryson also reasoned that because the temperature difference between the equator and the North Pole had increased, the zonal wind fields had strengthened, shifting the subtropical anticyclones towards the equator, and contributing to the Sahelian drought. Bryson's hypothesis is now disputed; cooling in northern latitudes is perhaps an effect rather than a cause of changes in the pressure patterns (Schneider and Mass 1975). Nevertheless, Bryson has had a beneficial effect in stimulating research into the complex problems of world climate.

3. The Prediction of Climate

a. Statistical Correlations

A global observing programme of WMO called the World Weather Watch (WWW) provides the data required to determine the state of the atmosphere at any given time, and to make predictions for the next 1 to 2 days, with broad outlooks for an additional 3 to 5 days. As the time span increases, the forecaster's skill diminishes until his predictions are no longer better than those based purely on persistence of existing conditions or on climatological average values.

To predict weather and climate over time periods of more than a few days, the statistical approach has often been used, extending the time and space correlations that are known to exist amongst meteorological series. One variant of this approach is based on the premise that a monthly/seasonal climate anomaly should have at least some slight effect on the climate of the next month/season at the same location, due to the time lag of the underlying surface in its response to the atmospheric anomaly. However, studies of this type have met with little success at least for seasonal forecasting (Kanestrøm 1975).

As a second variant, investigators may seek to correlate an anomaly in the condition of the underlying surface with:

(i) a climatic anomaly at the same location; or

(ii) a climatic anomaly in some other region, perhaps many kilometers away, and at some later time.

Case (i) is of trivial interest because the relation is so direct: if snow falls on a grass surface, for example, the heat budget is drastically modified. Case (ii), on the other hand, implies that there has been a change in the world pressure patterns, and is therefore of considerable importance particularly if such correlations could be used to predict climatic anomalies a few months ahead. In this connection, special attention has been given to the climatic effects of large-scale sea surface temperature anomalies. As an example, Namias (1970) has found that the relatively cool decade of the 1960's in the Eastern United States was associated with a relatively warm anomaly in sea surface temperatures in the North Pacific. However, one of the questions that needs to be answered is the extent to which the ocean is master or the extent to which it is slave to the atmosphere. This field of research is promising and should be encouraged, one of the practical applications being the development of hemispheric and world scenarios for food production.

As a third variant (Lamb 1965), systems have been devised for classifying daily air-mass types or daily weather patterns over a region. The annual frequencies of each type are then correlated with values of the climatic elements or anomalies.

Finally, there are methodologies which cannot readily be classified. In many such cases, the regression equations show statistical significance but they fare badly when applied to independent data. This is because: (a) there is difficulty in obtaining a random meteorological sample, one of the prerequisites for employing classical statistical theory; and/or (b) the regression equations are not based on physically plausible hypotheses.

The possibility of using statistical techniques to predict large-scale climate anomalies several months in advance is an attractive but still elusive goal. At a recent symposium, the participants agreed that there were too few scientists actively working in this field, and that there was need to develop several additional specialized research institutes around the world. The symposium was held in connection with the 16th General Assembly of the International Union of Geodesy and Geophysics (IUGG), at Grenoble, France in 1975.

b. Numerical Models

The numerical models used operationally to make short-range weather forecasts require data on the current state of the atmosphere. This information is obtained routinely from the WWW which includes more than 7,500 surface stations, 600 upper-air stations, and satellite observations. These data are used to construct the current three-dimensional fields (at 5 to 10 heights) of temperature, pressure, water vapour, wind direction, and wind speed. The governing equations are then solved for a series of discrete time steps (usually about 10 minutes in real time for each step), using finite differencing (grid squares of 381×381 km^2). Often included are the equations of motion, of thermodynamics and of water vapour, and the balance equations of heat and water at the surface of the earth.

When these models are started up from a very simple initial condition such as an isothermal atmosphere, and with idealized topography, they produce patterns that look like those observed on real weather maps, and the resulting climatological statistics also resemble real data. Some of the models which incorporate hydrologic processes can actually recreate the major rivers of the world. This leads to the speculation that the atmospheric effects of man-made changes (such as an increase in CO_2 concentrations, tropical deforestation, or introduction of a forest cover over a desert) can perhaps be simulated correctly, and a number of such simulations have been reported (Manabe 1975, Potter et al. 1975). The results have been exciting, but a number of technical questions must be resolved, including the following:

(i) How are the simulations to be verified?

(ii) How much scale resolution is needed?

(iii) How are radiative effects of clouds to be characterized?

(iv) How are the land surfaces (such as orography plus a patchwork of towns, farms, woodlots) of the world to be modelled as sources and sinks of heat and water?

A drawback with these simulations is their cost. Because the computer running time is only about 10 to 100 times faster than nature itself, the cost is so great that the number of climate simulations performed so far does not exceed 50. Consequently, many simplifications have been introduced, two well-known examples of simplified models being those of Budyko (1969) and Sellers (1973). In general, the problem is to couple the atmospheric general circulation to oceanic, sheet ice and land biosphere models in a realistic way but without excessive computer costs. The various interacting submodels are illustrated schematically in Figure 9 (Bolin 1975a). There are many couplings and feedback mechanisms, some of which have time lags of decades or even centuries. The processes are, in general, non-linear. A comprehensive review of the physical basis for climate and climate modelling, with special emphasis on the interactions between atmosphere, oceans, ice, soil, and vegetation, has been given in a recent report of the Global Atmospheric Research Programme (GARP) (Bolin 1975a).

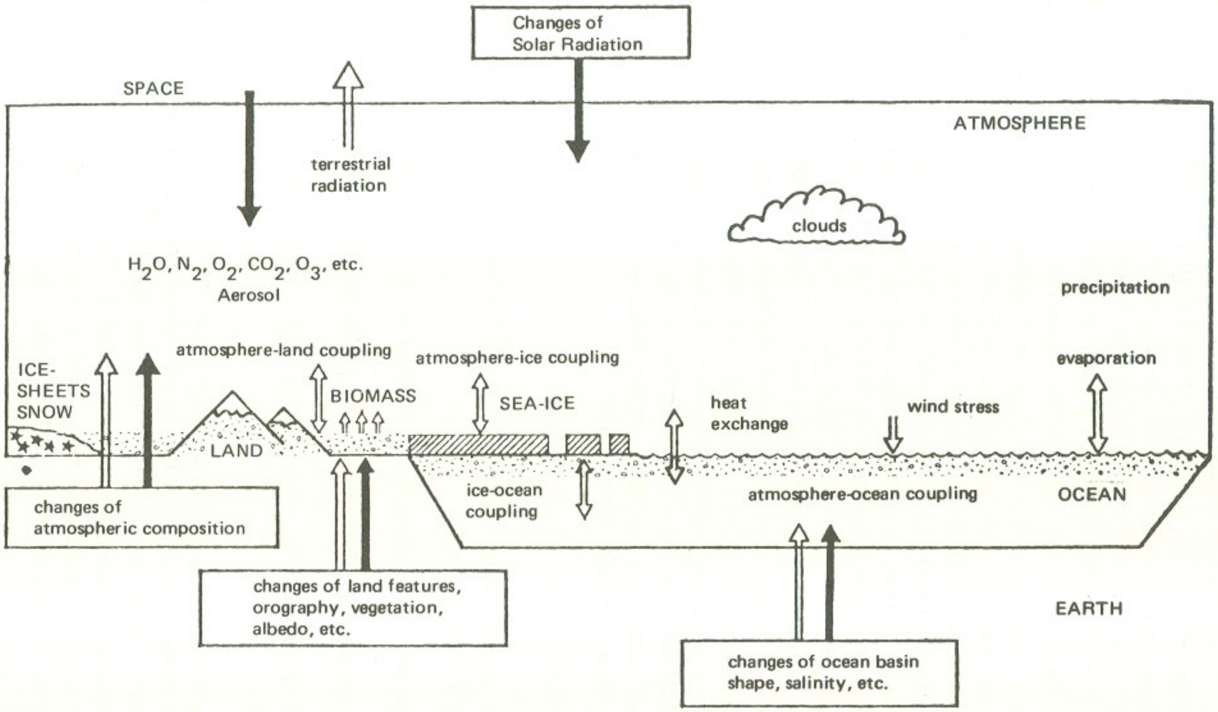

Figure 9 Schematic illustration of the components of the coupled atmosphere – ocean – ice – land surface-biomass climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes; biomass is represented by stippling (Bolin 1975a)

Some of the factors that may affect climate are external (astronomical geometric factors, changes in solar radiation, volcanic eruptions) and the behaviour of these factors is not affected by the state of the atmosphere. Other factors are internal (extent of sea ice, glaciers). Schneider and Mass (1975) have stated that 'perhaps the chief open question in climate theory' is the extent to which 'the statistics of the actual climatic system can be attributed to internal or external causes'.

Some of the astronomical factors (periodicities in orbital characteristics such as precession, eccentricity, and obliquity) operate on such long time scales (from 10^4 to 10^5 years) (Berger1975) that they are of no immediate concern. In a similar class are geophysical processes such as mountain-building and continental drift. Nevertheless, the study of such factors is of considerable practical importance. It would indeed be valuable if it could be established that ice ages were associated with particular astronomical and/or geophysical events (Weertman 1976).

On a time scale of years to centuries, the external factors that might influence climate include volcanic dust and sunspots. Schneider and Mass (1975) have created an 'index' reflecting the combined behaviour of these two factors, and have derived annual values of the index dating back to 1600 AD. This series has been introduced into a climate model to predict year-to-year variation in 'planetary radiative equilibrium temperature'. Although this temperature need not be the same as, nor even correlated with, the surface temperature in any given region, the similarity of Schneider and Mass' predicted values with temperatures inferred from ice cores, trees rings, and European temperature records is rather remarkable. Schneider and Mass emphasize the need for:

(i) better measurements of solar variability;

(ii) deeper understanding of the effects of volcanic dust on radiative heating rates in the atmosphere;

(iii) an improved reconstruction of the global surface temperature history;

(iv) improved parameterizations of atmospheric processes; and

(v) increased support for studies of the predictability of volcanic and solar activity.

In addition to the external forcing mentioned above, there are internal processes (see Figure 9) influencing climate. Paramount among these are those occurring in the world oceans. These vast bodies of water are part of the climate system that display considerable thermal and mechanical inertia. Numerical modelling of the oceans has only just begun, and there is still a lack of suitable data for model verification. Here it should be pointed out that the oceanic equivalent of the atmospheric cyclonic scale is only about 100 km (as compared with 1,000 km in the atmosphere), so that the observational requirements are severe. (A list of theoretical and experimental studies that need to be undertaken has been given in Bolin 1975a.)

An important question being raised is the degree of self-regulation (homeostasis) in the atmosphere. Could an ice age occur in the absence of a change in externalities? Is there a possibility of runaway processes or of large overshoots? It is a surprising fact that the earth's climate has changed so little over decades and even centuries, even though there is sometimes a great year-to-year variability. In this connection, the historical evidence on the length of time required to enter an ice age is confusing (tens of years or thousands of years?).

Research into these topics has centred around the concept of an 'almost-intransitive' system, a phrase introduced by Lorenz (1968). If all initial states of a system lead to the same set of statistical properties, the system is said to be transitive. If initial states lead to more than one set of statistical properties, the system is said to be intransitive. The third possibility is an almost-intransitive system, which occurs 'if there are different sets of statistical properties which a transitive system may assume in evolving from different initial states through a long but finite time span' (Bolin 1975a, Lorenz 1975). This last possibility, which could lead to cases of mistaken identity, has led to a rather broad discussion on the predictability of atmospheric processes. The word 'predictability' has been used in several ways and needs to be defined rather carefully. At least two sorts of predictions can be distinguished (Lorenz 1975):

(i) predictions of climatic sequences; and

(ii) predictions of the long-term statistics that might ensue if the boundary conditions were changed, for example, if there were a major increase in atmospheric CO_2 concentrations.

The extent to which climate is predictable in either of these senses is unknown. The consensus of a recent workshop (Bolin 1975a) was that: 'the fact that one can construct a climate model that embodies the totality of physical processes in a realistic way does not ensure that it can necessarily predict a unique sequence of climatic events – even in some statistical sense. The extent to which this kind of predictability is possible is yet to be established'.

4. Some Current Research Activities

a. Introduction

Information on climate, climate change, and climate modelling can be found in many publications (SMIC 1971, Stewart 1973, Bolin 1975a, 1975b, CIAP 1975a). A new journal, *Climatic Change*, edited by Schneider and published by Reidel Pub. Co., has just appeared, while two major workshops have been held in recent years (SMIC 1971, Bolin 1975a), as well as a number of symposia (WMO 1975a). The following sub-sections will therefore be restricted to a discussion of only three selected topics of current interest: the Sahelian drought, stratospheric ozone, and the CO_2 problem.

b. The Sahelian Drought

The Sahelian drought became perceptible in West Africa in 1965, reaching its peak in 1972 when rainfall was close to the hundred-year minimum in many parts of the Sahel. Although rainfall returned to normal in 1974, the effects of the drought have not yet disappeared.

The 'latest' drought always seems to be the worst, and in terms of its socio-economic impact, the Sahelian drought may indeed have been the worst in recent experience. However, hydrological data from the Senegal and Niger rivers reveal episodes of similar severity, one in 1910 to 1914 and another in 1940 to 1944 (Roche et al. 1975).

The human suffering in the Sahel has drawn public attention to the problems of arid and semi-arid regions; in fact, there will be a United Nations Conference on Desertification (General Assembly Resolution 3337 (XXIX)) in 1977. The scientific community has also been studying the problems of droughts and deserts, and there have been many recent publications (WMO 1975b). One of the most important meteorological investigations is that of Charney (1975).

The North African desert is a meteorological contradiction in the following sense. Although the surface temperature in summer is high, the region (the Sahara and Arabian deserts) is a radiative sink in summer (confirmed by satellite pictures). To maintain equilibrium, the air subsides and compresses, decreasing the relative humidity and cloudiness. Consequently, once a desert condition has been established, there is a positive feedback to maintain it. This much of the story is well known. However, Charney believes that there is a second mechanism of equal importance. As aridity increases, vegetation decreases, which causes an increase in the surface albedo, the ratio of the reflected and scattered solar radiation to the total incoming radiation. This increases the strength of the radiative sink at the top of the atmosphere and further feeds the process.

Charney has used a numerical model of the atmosphere to substantiate this hypothesis. When the albedo over North Africa was increased in the model from 14 to 35 percent, the inter-tropical convergence zone was shifted south several degrees of latitude and the rainfall in the Sahel was decreased about 40 percent during the rainy season.

Once this process has begun, other physical factors contribute to drought and desertification:

(i) wind erosion, caused by a reduction in vegetative cover, results in a decrease in germination of seedlings and an increase in desiccation of roots;

(ii) increased atmospheric subsidence, caused by the increased atmospheric dust load (see Bryson and Baerreis 1967), results in a decrease in cloudiness and precipitation; and

(iii) increased diurnal range of surface temperature and humidity, caused by a reduction in vegetative cover, results in a harsher microclimate for seedlings.

An important question remains to be answered. What causes a drought to end? In some cases, desertification may be almost irreversible. The Rajasthan desert in Northwestern India and Southeastern West Pakistan mày have been formed in this way (Bryson and Baerreis 1967). But in other cases, the dry spells come to an end 'naturally'. Why?

In conclusion, it should be added that the Sahelian drought was not purely a meteorological phenomenon. A number of socio-economic factors can also be cited (UNESCO 1975):

(i) a reduction in animal diseases in recent decades due to advances in veterinary science, resulting in an increase in livestock populations thus placing considerable pressure on grazing lands;

(ii) an increase in the number of watering places in recent decades through various engineering works; this has had the unwanted side-effect of large-scale degradation of adjacent pastures;

(iii) a lack of understanding by governments of the traditional ways in which the pastoral nomads were in equilibrium with their environment;

(iv) a lack of perception of the environmental risks to which the populations were subjected.

c. Stratospheric Ozone

The stratosphere contains small amounts of ozone, a gas that has a major effect on radiative transfer and thus on the general circulation, including large-scale vertical motions. Ozone also shields the surface of the earth from receiving a part of the incoming ultraviolet light. The possibility of a disruption of the stratospheric ozone balance is therefore an important question.

Ozone is created by the action of solar ultraviolet radiatiòn (200 to 250 nm) on oxygen, the main region of production being in the layer from 30 to 50 kilometers. Although produced at these altitudes and primarily in the equatorial region, the ozone layer usually has its maximum values in polar regions and at lower altitudes – the results of equator-to-pole transport processes. Destruction of ozone was at one time considered to take place simply through recombination with atomic oxygen. However, this process is relatively slow and calculations using it as a primary destruction mechanism tend to overpredict the amount of ozone. Other chemical reactions have therefore been proposed, including those involving hydrogen compounds (OH, HO_2), nitrogen oxides and, more recently, oxides of chlorine and bromine.

Comprehensive models describing the stratosphere must account for major singularities, referred to as 'stratospheric warmings'. These mid-winter explosive events are grossly at variance with climatological rates of heating and cooling. They are primarily polar phenomena. Large temperature increases (40 to 80°C) within a few days time are associated with a reversal of the basic circulation in the stratospheric polar night vortex from westerly to easterly flow. The sudden change in stratospheric temperature and circulation must have an important effect on the distribution of atmospheric constituents as well as on their chemical reaction rates.

Extensive reviews of the photochemistry of the stratosphere have been given (CIAP 1975b). The growing list of candidate threats to the ozone layer includes the following:

(i) high-flying aircraft (e.g., supersonic civil and military aircraft);

(ii) nuclear bombs;

(iii) halocarbons, such as 'Freon' (from aerosol sprays and refrigerants) and carbon tetrachloride;

(iv) nitrous oxides from fertilizers (McElroy 1975); and

(v) volcanic eruptions.

The effects of one or more of these are difficult to predict, partly because the stratosphere behaves dynamically; if ozone were destroyed at a particular latitude, the general circulation might adjust to such an extent that the global ozone distributions could not be predicted.

The special concern relating to (iii) and (iv) above arises from the fact that the time lag between ground-level release of a substance and its maximum effect in the stratosphere seems to be of the order of a decade. This long time lag, together with the fact that there is appreciable natural variability in the strength of the ozone layer (which makes it difficult to detect man-made changes) means that if no action were taken until a measurable impact on the ozone layer had been demonstrated, it would then be too late to avoid further effects.

The following programme (WMO 1976) should therefore be given high priority:

(i) additional monitoring of trace gases in the stratosphere (not only ozone but also N_2O, NO, NO_2, and chlorofluoromethanes);

(ii) establishment of monitoring networks for ultraviolet radiation; and

(iii) increased interdisciplinary research on the following topics:

(a) the coupling between stratospheric chemical composition, heating rates and circulation, taking account of tropospheric-stratospheric exchange processes;

(b) the influence on climate of changes in stratospheric ozone, involving quantitative treatment of the associated feedbacks using three-dimensional photochemical models;

(c) the biogeochemical nitrogen cycle, its possible modification due to man's activities and the implication for atmospheric chemistry.

(d) biological consequences of spectrum changes in solar ultraviolet radiation.

d. The Carbon Dioxide Problem

Since the beginning of the Industrial Revolution fossil fuels have been burned in increasing quantities. This has caused an increase in the concentration of carbon dioxide in the atmosphere. Various models and assumptions about fossil fuel reserves and consumption rates have been used in attempts to predict how far this trend will continue, and with what effect: some models suggest that atmospheric CO_2 concentrations could increase fourfold or even eightfold in the next 200 years.

The precise effects of such a massive increase are difficult to predict but they are likely to be of two main types.

(i) Climatic changes. The radiative budget of the atmosphere would be changed, causing changes in cloudiness, precipitation, and temperature. The numerical model of Manabe and Wetherald (1975) predicts that a doubling of CO_2 concentration would cause an average surface temperature rise of 2 to 3°C. However, the increase would not be distributed uniformly around the globe. Budyko and Vinnikor (1976) have suggested that global warming would reduce the pole-to-equator temperature differences, so diminishing the strength of the meridianal winds, reducing the transfer of water vapour from oceans to continents, and thus decreasing the rainfall averaged over all land areas.

No simulations of the effects of four- to eightfold increase in CO_2 have been undertaken, but it would be unwise to dismiss this possibility without exploration, particularly since the increasing burden of chlorofluorocarbons also affects the atmospheric radiation budget (Ramanthan 1975).

(ii) Increase in acidity of the oceans. A considerable part of the CO_2 added to the atmosphere finds its way into the oceans, and as more and more is absorbed the acidity of the sea is likely to increase gradually. The biological implications of this have not yet been examined.

Hafele and Sassin (1975) have suggested that the time required for a new energy production system to gain 50 percent of the United States market, starting from the 1 percent level, is about 60 years and in other parts of the world the time is likely to be even longer. This lends urgency to an assessment of the possible environmental effects of present day energy generation systems.

5. The Impact of Climate on Man

Living organisms have limits beyond which they cannot tolerate extremes of temperature, wind, and radiation. As the word acclimatization implies, however, most organisms are capable of some adaptation, a process which may involve

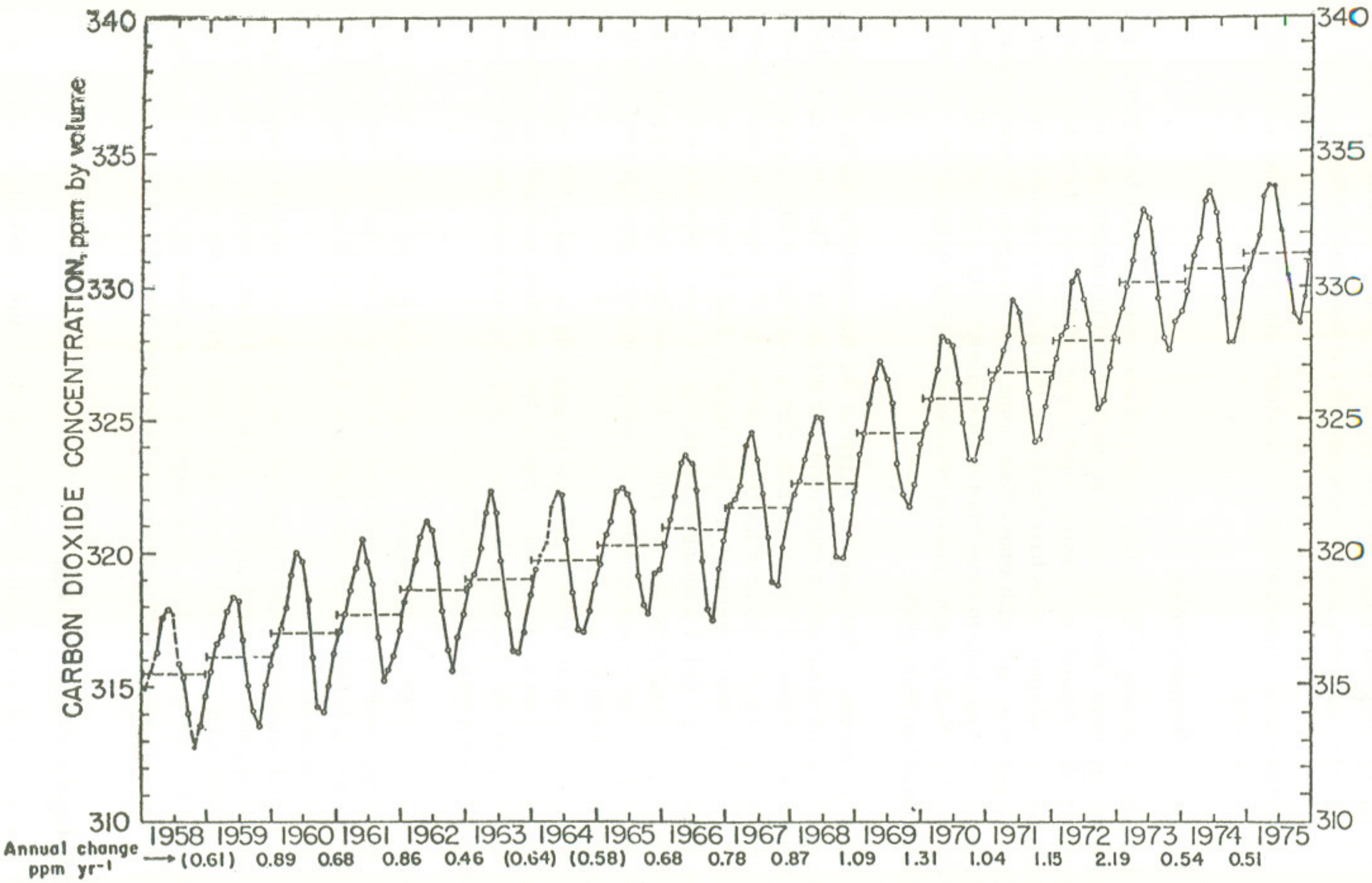

Figure 10 Changes in atmospheric CO_2 concentrations (based on Scripps 1974 manometric calibration)

physiological adjustments of the individual, or evolution of new ecotypes. The process may take place over times ranging from seconds to centuries, and there is quite often a lag between stress and response.

Ecosystems also respond to climatic change, both by adaptation of component organisms and by immigration of adapted species. Because of time lags, ecosystems may reflect past rather than present climatic conditions. Vegetation exhibits a degree of inertia dependent on: (a) its structure; (b) the extent to which it creates its own protective microclimate; and (c) the longevity and reproductive performance of its members. Ecosystems that developed during earlier and more favourable climatic conditions are sometimes fragile in the sense that fires, over-grazing, and forest cutting are likely to produce irreversible effects.

Climate seems to have its greatest impact on agriculture. The remainder of this section will therefore deal with that topic, although the fact should not be overlooked that nearly all of man's activities (agriculture, forestry, construction, transportation, and energy production) are climate-sensitive. For example, although the major decline in the anchovy harvest off the coast of Peru in 1972 was caused in part by over-fishing, there was also an oceanographic meteorological connection. The occurrence of the El Niño off the coast of Peru and a reduction in upwelling controls plankton production upon which the anchoveto feed (Wytki et al. 1976). These events were caused by climate anomalies and were associated with anomalies elsewhere around the globe (Flohn 1973, Flohn and Fleer 1975).

Climate and agricultural yields have fluctuated in the past and will continue to do so in the future, and climatic variability must also be taken into account when planning economic and social development. Other factors have an important impact on agriculture, such as the desire to optimize profits rather than yields. Although climate is not the only factor affecting yield, particular concerns for environmental managers are: (a) that year-to-year climatic fluctuations might become bigger than they have been in the last several decades; or (b) that the running-mean climatological values of temperature and other elements might change significantly; and (c) that these changes might occur too rapidly for man to adjust without major disruption.

Several international workshops on the subject of climate and food have been held recently: The Sterling Forest Workshop, at the Sterling Forest Conference Center in New York, in December 1974; The International Federation of Institutes for Advanced Study (IFIAS) Workshop in February 1975; and The Bellagio Conference sponsored by the Rockefeller Foundation in June 1975. Some common threads have emerged which can be woven together to yield the following recommendations:

(1) There is need for better understanding of the global organization of climatic anomalies, particularly those of vital importance to world agriculture.

(2) There is need for an improved world network for monitoring crop growth and yields. In some semi-arid regions, there is also a requirement for more climate stations.

(3) There is need to determine the carrying capacity of the world for various climatic scenarios. How much arable land exists? How could its use be optimized?

(4) There is need to develop contingency plans for unfavourable climatic episodes such as the 1933–1936 drought in the North American Midwest.

(5) There is need to accelerate research, building on IBP studies of novel food sources, into the development of new strains of crops with one or more of the following properties:

(a) more tolerance to drought;

(b) more tolerance to saline soils;

(c) increasingly efficient use of water, the supply of which will diminish in some regions regardless of climate trends;

(d) increasingly efficient use of solar energy; and

(e) adaptability to a shortened growing season.

(6) There is need to accelerate research on strategies to improve the collection and storage of precipitation in soils, and the prevention of evaporation from soils: such conservation techniques are especially needed in dry-land (nonirrigated) farming and grazing.

(7) There is need to consolidate current knowledge and to encourage further research on microclimatological techniques for ameliorating unfavourable macroclimatological conditions, through aircraft dusting of snow surfaces with soot to accelerate melting, and through the construction of shelter belts to decrease wind speeds and air drainage corridors to reduce frost frequencies. The potential impact of some techniques of weather modification is such that thorough theoretical research should always precede operational testing.

(8) There is need to undertake, and disseminate widely, analyses of food-climate policy alternatives at the national, regional, and global levels, so that a public debate on these crucial issues can be started. In this connection, special efforts should be made to publicize the view that the climate fluctuates, so that average values for the last 30 years are not necessarily good predictors for the next 30 years. As mentioned by Winstanley (1973), it is probably no accident that much of the economic development and population expansion in French West Africa took place during a period of abnormally good rainfall: in 27 of the 39 years from 1920 to 1958, rainfall was above the long-term average.

Finally, mention should be made of some recent recommendations for climate research (WMO 1975c), in which it is urged that high priority be given to the following data synthesis and observational tasks:

(1) the synthesis of synoptic data (since about 1950) into hemispheric and global sets that would be readily accessible;

(2) the synthesis of data on past climate, with emphasis on the need for international co-operation in the retrieval of data from indirect and 'proxy' sources;

(3) the establishment of long-term monitoring programmes for climate parameters such as the extent of sea-ice and snow cover, anthropogenic heat releases, biomass of trees, and solar radiation at the top of the atmosphere; and

(4) specific observational studies for the development of parameterization techniques in numerical simulations.

Remote sensing is already important and will play an even greater role in years to come (Kunkel et al. 1975). Since 1968, information on snow and ice cover and on sea surface temperatures has been collected from satellites, although there is as yet no central intergovernmental repository for synthesized data. By the mid-1980's, vertically-integrated estimates of the atmospheric burdens of a number of trace substances should be possible. Another application of remote sensing is in the determination of crop acreages and crop yields. Because existing information is inadequate in many cases, the regression equations between yields and various climatic factors need to be improved, not only for predictions of current harvests but also for use in climatic scenarios. To close this gap, a research programme called LACIE (Large Area Crop Inventory Experiment) has been started (Hammond 1975). The objective is to use satellites to estimate the acreages of selected crops, and to develop better regression equations relating yield to current climatological data.

D. POLLUTANTS IN THE ENVIRONMENT

1. Background

Man has been polluting his environment since he began to live in large settlements, to burn fossil fuels, and to apply technology to the needs of city dwellers. The process accelerated during the Industrial Revolution with the introduction of steam power for factories and with greater concentrations of populations in manufacturing centres. The number and variety of pollutants increased markedly with the development of modern chemical technology in the last century.

Until quite recently these undesirable results of man's activities were accepted by most observers as the inevitable concomitant of technological advance. The arousal of a public conscience in these matters is of quite recent origin. It was sparked by unfortunate episodes where appreciable numbers of persons became ill or died from the effects of pollutants. It was also stimulated by articulate prophecies of impending disasters such as that of Rachel Carson in 'Silent Spring' published in 1962.

Public interest in these problems was focused by the United Nations Conference on the Human Environment held at Stockholm in 1972. Two of the recommendations of that conference were:

Recommendation 73 – 'It is recommended that Governments actively support, and contribute to, international programmes to acquire knowledge for the assessment of pollutant sources, pathways, exposures and risks and that those Governments in a position to do so provide educational, technical and other forms of assistance to facilitate broad participation by countries regardless of their economic or technical advancement.'

Recommendation 80 – 'It is recommended that the Secretary General ensure: (a) That research activities in terrestrial ecology be encouraged, supported and coordinated through the appropriate agencies, so as to provide adequate knowledge of the inputs, movements, residence times and ecological effects of pollutants identified as critical.'

These recommendations describe activities to be undertaken by the United Nations Environment Programme in that part of the action plan called 'Earthwatch'.

Pressure to undertake research and assessments of the effects on the environment and its inhabitants resulting from the release of pollutants has understandably increased. Considering the number of actual and potential pollutants, receptors, and environments, the requirements for investigation are enormous. Guidance is needed on which problems are the more urgent and on how to conduct research most economically to yield the most relevant results.

Perceiving this need, SCOPE began in 1971 to consider a project on Ecotoxicology to be conducted by a Preparatory Committee. The membership and activities of that Preparatory Committee are reported in Appendix C and Chapter 5.

Many other aspects of the possible effects of chemical substances released into the environment rightly attract international concern. The after-effects of both accidental and deliberate discharges such as fertilizers or pesticides, cannot properly be understood or predicted without thorough studies of the pathways of those materials in the environment, their chemical transformation by interaction with environmental components or through biological action, and their impact on living targets. Because of their complexity, the pathways need examination as a part of analysis of the structure and functioning of ecosystems as a whole. The interaction of pollutants with soils, for example, may be affected by the chemical composition, physical structure, water concentration and composition, absorption capacity, humus content, and the microbial, fungal, and animal populations of the soil. Knowledge of these factors, except for a small number of intensively studied areas is gravely inadequate. Similarly, while there is considerable knowledge about the impact of chemicals on selected living targets, less is known about their impact on ecosystems. Climatic, topographic, hydrological, and edaphic variables combine to alter the significance of a level of exposure of a particular target to a particular pollutant. Even where apparently similar ecosystems are exposed, subtle variations in their structure and dynamic processes may give very different end results. Nonetheless, the basic logic explored by the SCOPE group on ecotoxicology should apply in such pathway studies and in analysing the responses of ecosystems.

2. The Concepts of Ecotoxicology

Ecotoxicology is defined here as follows:

Ecotoxicology is a discipline which studies the impact of toxic agents on ecosystems, in contrast to classical toxicology which deals with the toxic effects of chemicals on individual organisms. It involves the estimation of doses, and the related effects, of any activity which may contaminate the environment. Ecotoxicology uses the results, values, and estimations of classical toxicology and incorporates these into studies of ecosystems.

Some readers may find it difficult to understand or accept the term ecotoxicology. They may prefer to think of it as the study of the total impact of releasing pollutants to the environment. Part of the difficulty arises because toxicological data generally relate to the impact of specified substances on individuals or populations of particular species. The response of an ecosystem is determined by the integration of these effects and is difficult, if not impossible to measure directly.

Impact on human health and well-being is most clearly appreciated, but other living things may be affected and there is an expanding awareness that these non-human effects must be included in the assessment. These effects must be assessed not only locally but on a regional or global scale. It is increasingly accepted that there should be an assessment of not only the acute effects of high doses, but also the late effects of chronic exposure to low levels (including carcinogenesis, mutagenesis, and teratogenesis).

The release of substances to the environment may be intentional, as it is with pesticides, food additives, pharmaceutical products, and antibiotics, which nonetheless have unforeseen side-effects, or unintentional, which is the case with many industrial chemicals. The releases usually occur as a result of man's industrial or commercial activities although some pollutants are released as a result of phenomena with no human involvement. As an example of the latter, some toxic substances (mycotoxins) are produced by fungi which infest food and food grains, and can be a considerable problem in areas with high temperature and humidity.

The pollutants are usually substances that owe their toxicity to their chemical properties or to a content of radioactive atoms.

For the past twenty years the United Nations Scientific Committee on the

Effects of Atomic Radiation (UNSCEAR) has been reporting on releases of radioactive materials to the environment and assessing their long-term effects on man on a global scale. Many of the ideas and techniques developed by that committee, as well as those of the International Commission on Radiological Protection (ICRP), can be applied to assessing the impact of environmental pollution by chemicals. To do this requires consideration of six elements of the problem.

a. Amounts Manufactured and Released

The potential for harm of a given pollutant depends on the amount of it in use. Some information on this subject has been made public, but it is difficult to obtain more for several reasons including ignorance, security (national or economic), or embarrassment.

b. Persistence in the Environment

Substances will have more widespread effects (in both time and space) if they persist for long times without a chemical or physical change which reduces their toxicity. In this context, persistence has been defined as the length of time a substance remains in a recognizable chemical form. Obviously the persistence will depend on how rapidly change takes place after release to the environment. The most common changes result from hydrolysis, oxidation, photochemical reactions, or biochemical reactions in metabolism. In addition to changes that reduce the toxicity one must consider conversion to products that may be more toxic or more persistent; examples are the conversion of DDT to DDE and inorganic mercury to methyl mercury.

c. Transport in the Environment

Since one of the objectives of ecotoxicology is to calculate the exposure of a receptor resulting from unit release of a pollutant, the nature and magnitude of the exposure routes must be known. Meteorological and hydrological phenomena play important roles in transport, particularly in its early stages. Air transport due to winds and diffusion leads to direct exposure of the receptor by inhalation. Air transport coupled with dry surface deposition and wash-out in rain introduces the airborne pollutant into soil, surface waters, and ground water. In soil the pollutant may be retained by adsorption: if it is released into water its transport is chiefly a hydrological process although some of it may escape to the atmosphere and be recycled into the hydrosphere. Information about this geochemical cycling may come from a knowledge of pollutants of geological origin such as heavy metals, oxides of carbon, sulphur, and nitrogen as well as airborne dust particles.

The other important route of environmental transport is through biological processes or food chains. Plants take up chemicals through their leaves and roots while animals absorb them by inhalation or ingestion. Thus the coefficients of absorption by these routes must be quantified. The time of retention in organisms also influences the accumulation; thus a high rate of uptake and a long retention time will result in a bioconcentration of the substance. In addition to these metabolic factors the dietary habits of the receptors must also be known to assess the exposure through food chains.

The number, complexity and interactions of these paths and processes lead to difficulties of conceptualization and overall assessment so that assistance is required from modelling. Mathematical models can assist in selecting critical paths for which simplified calculations are adequate and they can identify the variables with the greatest quantitative importance. These identifications are a useful guide to monitoring and to quantitative studies of critical processes.

d. Metabolism in the Receptor

Under this heading are included the intake, uptake, retention, tissue distribution, and metabolism of the pollutant in the receptor. It also includes the basic mathematical formulations for calculating residence times in the critical tissues of the target organism.

The appropriate concepts as well as most of the mathematical procedures and much of the basic data for humans have been assembled by the International Commission on Radiological Protection (ICRP) for calculating radiation doses resulting from the intake of radioactive compounds by 'reference man'. Similar data are required for other organisms that form part of the food chain or are themselves target organisms. These data used by these procedures make it possible to calculate tissue dose rates or integrated doses.

e. Dose-Effect Relations

Much basic information about the relative toxicities of different substances to different species can be obtained from classical toxicology which involves laboratory studies of specific effects on homogeneous populations under controlled conditions. One important objective of such studies should be to identify the most appropriate independent variable (dosage) – should it be the amount of toxin administered, the amount retained, or the time integral of concentration in the body or an organ thereof? Plots of the results may often show the familiar sigmoid curve with a threshold, a finite dose with a negligible effect.

These studies must then be extended into the field by epidemiological studies where the populations are not homogeneous and the conditions are not controlled. All effects must be scored and more than one pollutant may contribute to or diminish the observed effect. Under these conditions plots of the results may more frequently approximate a linear dose-effect relation with no threshold. In the event of doubt it may be prudent to assume such a dose-effect relation when calculating risks and acceptable levels of dose for protection of populations against undesirable effects.

In designing dose-effect experiments and surveys, as well as in analysing and presenting the results, use must be made of the most appropriate statistical procedures and probability theory.

f. Assessment of Environmental Impact

The information about environmental persistence and transport coupled with numerical descriptions of metabolism in the receptor permits calculations of dose rates and integrated doses. These will vary from one member of the exposed population to another but estimates may be made of the mean dose to a given population. When the mean dose is multiplied by the estimated risk and the size of the population, the total response can be calculated. Not only must the immediate response be evaluated but also the future response insofar as it is possible. Relevant concepts for this exercise are the dose commitment and harm commitment evolved by UNSCEAR. Setting out to make these integrations into the future ensures that the total effects of pollutant releases will be considered.

It would be useful to identify observations and measurements of environmental variables that could be made to check the numerical predictions; for this it is desirable to identify accumulator and indicator organisms. Whether it is possible to identify environmental variables appropriate to a large number of pollutants appears doubtful, but many specific examples can be found and from a collection of these some general principles may emerge.

To illustrate by example what is meant by 'ecotoxicology', there is provided in Appendix D a summary of the ecotoxicology of methyl mercury; it indicates what information is required and demonstrates how it may be used. The summary shows that in practice there are two critical paths leading to an intake of methyl mercury by receptors:

(i) Methyl mercury contamination of food (usually grain).

(ii) The entry of inorganic mercury into a body of water.

Path (i), which is direct and simple, has led to the poisoning of seed-eating birds, domestic animals, and man from eating cereal grain dressed with organic mercury compounds. Knowing the concentration in the grain and the amount of grain eaten per day, one can calculate from the retention equation for methyl mercury in the receptor, the body content at any time following the beginning of consumption, as is done for internal radioactive contamination. The correlation of these body and tissue contents with neurological symptoms permits the construction of dose-effect curves followed by the calculation of risks and maximum permissible levels.

Path (ii) is more complex and correspondingly more difficult to evaluate. As Figure 17 shows, the most important chain of events, following the contamination of a body of water with inorganic mercury, comprises the following steps:

(1) Deposition of inorganic mercury in the bottom sediments.

(2) Conversion of inorganic mercury to methyl mercury by the action of microorganisms.

(3) Release of methyl mercury to the water.

(4) Uptake of methyl mercury by fish:

(a) directly from the water through the gills;

(b) indirectly through food (plant or animal) that has already taken up methyl mercury.

(5) Selective concentration of methyl mercury by metabolic processes in the fish.

(6) Eating of the contaminated fish by man or other receptors.

The most important link in this chain is step 2, and, unfortunately, it is the least well known quantitatively. This difficulty is aggravated by the near impossibility of measuring the very low concentrations of methyl mercury which occur in natural waters. Otherwise realistic calculations of the accumulation of methyl mercury in fish are feasible. Knowing this the accumulation of methyl mercury in the eater of the fish can be calculated in the same manner as for path (i).

In canvassing the steps involved in an ecotoxicological study, as illustrated in Appendix D, it should be recognized that the information available on methyl mercury is superior to that in hand for most other toxic substances.

g. *Analysis*

Basic to studies of ecotoxicology (and monitoring) are the feasibility and reliability of analysis for pollutants and pollutant residues in environmental media. In fact, doses cannot be determined without adequate analytical methods. This was recognized very early in the development of the programme of SCOPE, and a working party under the chairmanship of W. Gallay was set up to study and report on this problem.

A small group of experts was gathered to consider the merits and drawbacks of various existing methods of analysis for each of the many pollutants involved. The report of the working party was published as SCOPE 6, 'Analytical Methods for Selected Pollutants' (SCOPE 1975b). Where possible, in addition to a sophisticated method requiring expensive equipment and highly trained analysts, a simple method yielding adequate precision and accuracy was also included. Where feasible, methods were chosen for a pollutant in air, water, and biological media. It is expected that further work in this field will continue with the addition of further pollutants, and possible revision of the methods already published.

E. ECOSYSTEM PROCESSES

As Chapter 1 states, the ecosystems of the world have been modified extensively by man over the past million years and this alteration has in turn affected the interplay between the world's flora and fauna and the non-living environment. Because many of the features of that non-living environment, including the composition of the atmosphere, the structure and chemistry of the soil, and the levels and cycles of many elements and compounds, are the product of life and are vastly different from the situation on the lifeless earth, man's recent modification of the world's ecology carries with it the potential to perturb these features and processes. Whether or not this is a real problem is less easy to state and depends on critical, quantitative analysis of the composition and dynamics of ecosystems and of the degree of their modification by man.

There is urgent need for a practicable and quantitative approach to ecosystem dynamics in order to give more precision to this analysis and to provide a better basis for predicting trends. The ICSU-sponsored International Biological Programme (IBP) provided a great stimulus to the study of ecosystem structure and function and developed a firm basis for further ecological research.

Because ecosystems traditionally utilized for agriculture are now being intensively studied by FAO and many governmental, non-governmental, international, and national organizations, SCOPE has given special attention to managed natural systems. These have received relatively little attention, yet when they are utilized by man they tend to become rapidly destabilized, with associated severe, and sometimes essentially irreversible changes in their physico-chemical environmental attributes and in their biological characteristics. Considerable interest has been expressed in this subject by UNESCO, whose 'Man and the Biosphere' (MAB) programme contains a number of projects related to developing a better understanding of natural ecosystems, and a sounder scientific basis for their long-term management. SCOPE joined with the MAB programme in an evaluation of present knowledge of the patterns of change which occur in terrestrial ecosystems, and of the way in which this knowledge could be applied to the management of natural ecosystems (Chapter 5 and Appendix C).

The processes of ecological succession involve the sequential change in the species occupying a particular site. There is a close link with the evolutionary processes which continually modify the genetic constitution of the organisms involved in these ecological dynamics. Like successional processes, genetic evolution has been modified by man. Modern cultivars are selected lines with a very narrow genetic base, raised in environments whose inherent seasonal variation in soil moisture, nutrient levels, and competitive pressures is further reduced by management. Today, selective plant and animal breeding is being speeded up as the need for enhanced productivity in continually changing agricultural situations mounts. This effort needs, however, to draw on a large pool of genetic variability, much of it in natural or semi-natural habitats where the wild relatives of cultivated plants and domestic livestock survive or in areas where agriculture continues to use primitive, obsolete, or special genetic stocks. SCOPE has not concerned itself directly with these vital issues because they are the object of a major FAO programme, MAB Project 8, and activities supported by IUCN and UNEP, but research drawing upon ICSU expertise will certainly continue to be necessary, and as such, finds its place in Chapters 5 and 6.

The understanding of both successional processes and genetic conservation is important to the management of arid lands under rapid transformation by irrigation and drainage. In these situations the changes are rapid and massive. This process forms the theme of Section 2 of this chapter, and is examined as an example of drastic alterations by intensive management of soil and water.

1. The Analysis and Modelling of Successional Change

a. Present Concepts Regarding Ecological Succession

Classical concepts of ecological succession involve two key assumptions:

(1) that species replacement during succession occurs because populations tend to modify the environment, making conditions less favourable for their own persistence and leading to progressive substitutions, and

(2) that a terminal stabilized system, the climax, finally appears and is self-perpetuating, in equilibrium with the physical and biotic environment.

This view of ecological succession, based largely on observed spatial vegetational zonation which had occurred over centuries, and on patterns of revegetation on abandoned farmland, has been generally accepted by the ecological community following the pioneer studies of Clements and others even though obvious exceptions to it exist. Tansley (1935) and others indicated in general terms while Egler (1954) suggested more formally that the classical model of succession may not apply in all situations. Egler referred to the classical model as 'relay floristics' and suggested that, in many cases, the 'initial floristic composition' following a perturbation may dominate the entire pattern of succession; that is, unless species persisted through the perturbation, or were able to enter the perturbed site shortly afterwards, they would not be represented in the community that developed.

Evidence has gradually accumulated to suggest that the initial floristic composition concept may have much wider applicability than envisaged by Egler (Colinvaux 1973, Drury and Nisbet 1973, Horn 1974). Recently, Connell and Slatyer (1976) proposed an overall system of successional processes which incorporates the possibility of both the relay floristics and initial floristic composition pathways operating independently or in combination, and in addition includes a pathway in which succession is truncated short of the expected climax composition. These modifications clearly make the successional concepts more useful in understanding the properties of managed ecosystems, especially those being held in something akin to a 'steady state' and being managed for a sustained yield.

In Figure 11, various pathways are clearly indicated, and likely effects of perturbation, at different stages in each pathway, are also shown. The basic dichotomy between the classical 'relay floristics' concept (pathway 1) and the other models (pathways 2 and 3) is reflected in the immediate divergence of the pathways. In Model 1, referred to by Connell and Slatyer as the 'facilitation' model, the classical replacement pattern occurs, successive suites of species which

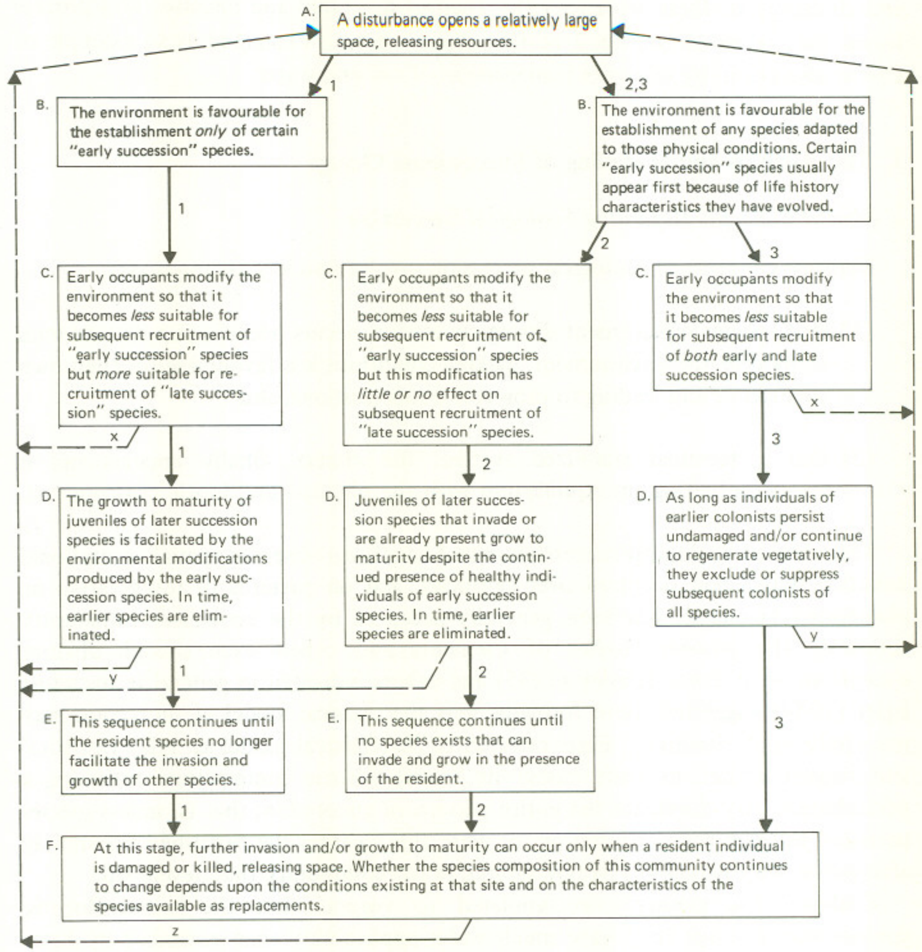

Figure 11 Three models of the mechanisms producing the sequence of species in succession. The dashed lines represent interruptions of the process, in decreasing frequency in the order x, y, and z. Pathway 1 is referred to as the 'facilitation' model; pathway 2 as the 'tolerance' model, and pathway 3 as the 'inhibition' model (from Connell and Slatyer 1976)

occupy the site tending to make the environment less favourable for their own existence and more favourable for their successors to invade and grow to maturity. In Model 2, the 'tolerance' model, environmental modifications induced by early colonists may neither increase nor decrease the rates of recruitment and growth to maturity of later species. The latter appear later because they either arrived later or, if present directly after the perturbation, had their germination inhibited or their growth suppressed. In contrast to the 'facilitation' model, in Model 3, termed the 'inhibition' model, the early occupants rather than facilitating progressive occupancy by other species, inhibit the invasion of other species either by pre-empting available space through physical occupancy alone, by physical competition, the use of allelopathic substances, or other effective means. This inhibition has the effect of truncating the succession at a stage that would generally be regarded as being dominated by non-climax species such as shrubs rather than trees (Niering and Goodwin 1974). Later succession species may only be able to enter the site when the inhibitory species are damaged or killed. If this occurs during a subsequent pertubation, the new succession may well follow a different pathway, avoiding a repetition of successional truncation.

In essence, the Connell and Slatyer concepts are based on the premise that the presence of a particular species in a community is dependent on the product of two probabilities; the first being the probability of a propagule being available at a site – a function of the ability to survive a perturbation or to reach the site by appropriate dispersal mechanisms; and the second being the probability of the propagule being able to become established at the site – a function of the environmental requirements of the species, its adaptive ability, and its reproductive strategies in relation to the prevailing environment.

The factors determining these probabilities are influenced by the size of the area perturbed and the frequency and severity of the perturbation, but propagule availability, in particular, is increasingly dependent on dispersal characteristics as both the area and severity of the perturbation increases. By comparison, establishment and/or persistence of a propagule is more related to degree of perturbation than to area. Plant species differ widely in their ability to persist as seeds, in their ability to become established or persist in exposed or protected locations, and in their competitive ability to obtain water and nutrients.

Just which of the available species are successful as colonizers, as invaders, or as dominants in various stages following perturbation will therefore depend on their adaptation to the physico-chemical site characteristics, on their competitive and other interactions with the other species in the community, and on their own life-history characteristics. There is, however, now significant evidence indicating how each model might operate, and how different pathways might be followed depending on the intensity, frequency, and scale (in terms of area) of a particular perturbation. The model also incorporates the concept of truncated succession, a phenomenon that many ecologists have observed but which has seldom been explicitly included in any general conceptual framework for succession as a whole. Overall, this general framework appears a useful basis for viewing successional processes, and one which lends itself to the development and use of mathematical models of successional processes.

b. Methods Available for Modelling and Predicting Successional Patterns

In recent years the application of several powerful modelling procedures to ecological processes has stimulated research into ecological succession in general, into the underlying processes involved in succession, and into the possibilities of providing a sounder ecological basis for the development of management strategies for natural and near-natural ecosystems.

Amongst these procedures, those involving the application of Markov processes to problems of ecological succession (Waggoner and Stephens 1970, Horn 1976) have stimulated most interest because a number of successional sequences appear to provide the ingredients for first-order Markov models and such models have desirable attributes for ecological studies and for management purposes.

A Markov process is one in which the future development of a system is determined by the present state of the system and is independent of the way in which that state has developed. A first-order Markov chain comprises a two-dimensional matrix (transition matrix) in which certain values of input parameters are converted to output values using specified probabilities (transition probabilities).

For example, Markov models are relatively easy to derive (or infer) from successional data, and the presence of the Markov property can be tested explicitly. Secondly, the models do not require deep insight into the mechanisms of dynamic changes, but can help to pinpoint areas where such insight would be valuable and hence act as both a guide and stimulant to further research. Thirdly, the basic transition matrix, which is the effective core of the models, summarizes the essential parameters of dynamic change in a system in a way which few other model families can achieve. Fourthly, the results of the analysis of Markov models are readily adaptable to cartographic presentation, and, in this form, are frequently more readily presented to, and understood by, resource managers. Finally, the computational requirements of Markov models are modest, and can easily be handled on small computers, or, for small numbers of states, on hand calculators.

In addition to these features, several interesting analyses of the models can be conducted which provide important information for the functionally oriented ecologist, and to the ecosystem manager. For example, analysis of the transition matrix leads to estimates of the time over which each successional stage can be expected to persist; the time to reach a climax composition, and the likelihood of the succession being truncated at a compostion which would traditionally be regarded as sub-climax. All of these attributes are of direct relevance to ecosystem structure and function and to management strategies.

There are also a number of disadvantages to the use of Markov models in ecological succession. In particular, departures from the simple assumptions of stationary, first-order Markov chains, while conceptually possible, make for disproportionate degrees of difficulty in analysis and computation. Also, the complete data sets necessary for the construction of transition matrices, and for subsequent validation of the models, are seldom available, so recourse must be made to other procedures to obtain the necessary information. There is also the concern of the functionally-oriented ecologist that a relatively coarse Markovian transition matrix, with its strongly stochastic character, may mask a number of key ecological processes.

The first of these problems may limit the application of Markovian models to a greater extent than is foreseen at the present time, but, until more models are developed and tested, the degree to which successional sequences conform to the requirements of stationary, first-order chains cannot be predicted. The second problem is very real for ecological systems containing long-lived organisms, since historical records are relatively short.

It is largely for these reasons that functional types of models, sometimes referred to as stand models (Leak 1970, Botkin and Miller 1974) have also created wide interest. The major advantage of such models is that they do not require long historical data records for parameter estimation, using instead basic physiological attributes of the species under consideration, which can often be inferred if not available from direct observation. Furthermore, the output from the model can be applied to a number of transformations and interpretations, so that the model user can present output in the same fashion that he would use actual data. Indeed, the model lends itself to experiments which could include management questions related to harvesting and grazing frequency, fertilizer addition, and related practices. This has implications of direct value to management.

However, testing of these models still presents difficulties, and a major disadvantage is that they use a great deal of computer time. Indeed, they represent a quantum leap in computer use in ecology, generating computer hardware problems in all but the most advanced computer centres.

Other procedures include the use of multi-variate analysis (Austin 1972) and of ordinary linear differential equations (Shugart et al 1973), each of which has particular advantages when applied to particular problems.

The advantages of the straightforward Markov model, particularly in relation to computer requirements, are such that its application to studies of ecological succession warrants detailed examination and exploration. The main obstacle in proceeding rapidly with a Markovian model is likely to be the absence of comprehensive data sets with which to construct the transition matrices. Other techniques, perhaps stand models in particular, may be used to generate the necessary data for the transition matrices, thereby reducing the amount of computer capacity and time associated with the sole use of a stand model, and enabling the construction of a Markovian model with its attendant attributes, but with desirable functional elements implicitly included.

c. *Application to Management of Natural and Near-natural Ecological Systems*

From the foregoing it is evident that the effective application of ecological knowledge to problems of ecosystem management requires the utilization of a variety of information – ranging from historical records through basic ecological research, to data from management – and also requires a high degree of interaction between the ecologist and the manager. In turn the ecologist interacts with a variety of other specialists, particularly in experimental design and interpretation, model building, and validation; and the manager interacts with those who influence his selection of management goals and constrain his management strategies.

In Figure 12 a general scheme, identifying the role of the ecologist, both in his specialist activities, and as an adviser to management, is depicted. Following the formulation of management aims, the first step for the ecologist is to assemble all available information on the system under study and on ecologically relevant systems elsewhere, including basic descriptive information as well as the effects of various management practices where these have been documented. Experiments may have been conducted in the region, and there may be a fund of anecdotal

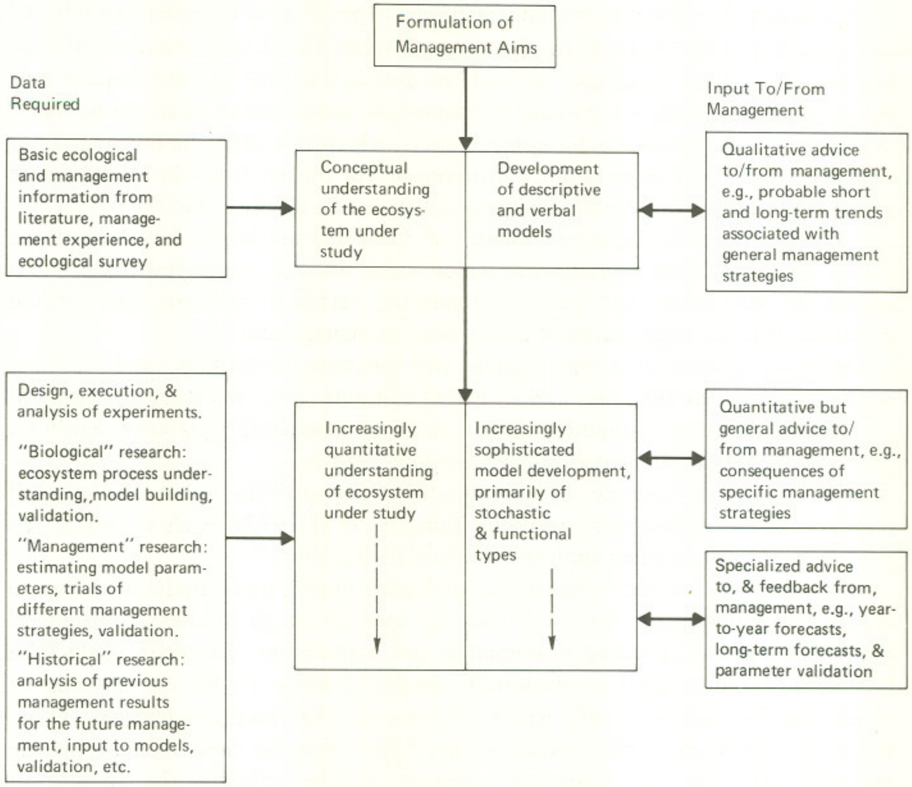

Figure 12 A schematic representation of the role of ecologists in producing ecosystem models and in giving advice for management purposes

information. To use such local background information is usually much more effective, in a benefit-cost context and because time is usually an important consideration, than to collect similar information afresh.

At this stage, a simple model can usually be built which incorporates existing information about the components of the system, and predicts the variables (such as wood production, meat production, or maintenance of a cerain series of desirable species) in the objective function defined by the manager. The best use should be made of the manager's own experience, and existing knowledge about the behaviour of ecosystem components should be assembled from local literature and local experts. This quick model may take the form of a transition matrix of vegetation types where the transition probabilities can be defined, or of a functional model of each type separately. In either case, attempts should be made to associate error estimates with the model inputs, and hence with the outputs. With this model, the manager may then proceed to estimate the short-term effects of the different practices he is considering, in terms of the selected objectives, and choose that practice which tends on average to move the objective function in the desired direction.

If the model is in the form of a transition matrix, the objective function will need to be rephrased in terms of desirable mixes of successional stages, including perhaps their spatial configuration in the area. A functional model, if that seems most appropriate, may often be simplified by assuming that direct species to species interactions among the plants may be ignored as a first approximation, and that each species may be modelled as being influenced by, and influencing, its abiotic environment.

This quick model, apart from the estimates derived from general regional background information, may also require information about the initial state of the system. In the case of the transition matrix type of model, this may be satisfied by the area of each successional stage. In a functional type of model, more detailed information about each of the vegetation types present may be called for.

It is not suggested that a model of this sort should be used for more than short-term prediction. The manager may act on the assumption that it is reliable (particularly where no more direct information is available), but must remain alert for error, monitoring the actual effects of the practices on the ecosystems in question. Then, by providing new inputs to the model, and obtaining a set of new predictions, he can modify his management strategy by trial and error to optimize his objective function. In other words, management should proceed interactively with the model.

The degree to which this initial quick model should be improved will depend on how important longer-term predictions are, and what resources are available. Additional sophistication of the model itself, its conceptual formulation and implementation, may need relatively little effort, compared with the collection of the extra data needed. To estimate new parameters for a model may call for considerable resources, and such an effort may only be justified by the need for a sound long-term management strategy. In any case, a first step will be to conduct sensitivity tests on the initial model to determine where the benefits of improved precision, from the point of view of the objective function, will justify the effort and resources required.

Apart from the building of the improved model and the collection of additional data, validation is also a problem. Since, by its nature, the model is at least in part new, this will need to be done afresh, preferably by new observations within the management area – observations, of course, which should not be associated with those used to estimate the parameters of the model. Validation will add to the time for model development, and again emphasizes the fact that ad hoc development of a sophisticated model will be worthwhile only if much hangs on it, and if long-term predictions are needed. If the validation can be replicated, it will have the advantage of providing unbiased error estimates for the model predictions.

It is clear that, if an analogous situation has already been modelled, a great deal of time and effort can be saved by adopting an existing model. However, a warning must be sounded. Unless that model has parameter estimates derived from similar material, and unless it has been validated for systems covering the same range, to accept its predictions will be an act of faith. It may be better to establish new, replicated, validation tests within the management area, and to use the predictions only after validation is achieved.

d. Conclusions and Recommendations

A full list of conclusions and recommendations is given in the main report of the MAB/SCOPE Workshop. The main conclusions at this stage are:

(i) Rapid advances have been made in recent years in both theory and experiment in the general level of understanding of ecological succession. In particular, a much better appreciation now appears to exist of the interplay between different successional patterns, the effect of perturbations on the observed patterns, and on the phenomenon of successional truncation in which long-term site dominance is achieved by species which might normally be assumed to be early succession, sub-dominant species.

(ii) Knowledge of successional patterns can provide a useful basis for developing models of direct relevance to the management of natural communities such as forests, rangelands, and lands set aside as biosphere reserves. Conversely, patterns of natural succession are of very limited relevance to the problems of managing ecosystems in which human intervention has markedly altered the physico-chemical environment and the biological species composition.

(iii) A veriety of techniques are available for modelling purposes. Of the techniques with stochastic properties, Markov models have been used successfully in several studies and appear to offer considerable scope for development and application. Of the techniques based on functional attributes, stand models which permit simulation of primary stand attributes also have considerable potential. However, no single approach can be generally recommended and all techniques have disadvantages which preclude their use in different situations.

(iv) Effective contributions to management require interaction between ecologists and managers. In turn, it is essential that the ecologist interacts with a variety of other specialists, particularly in experimental design, data interpretation, model building, and model validation; and the manager interacts with those individuals and agencies that influence his selection of management goals and constrain his management strategies.

The main recommendations at this stage are:

(i) Further work on ecological succession should be encouraged with a view to providing a thorough understanding of successional dynamics, and the interrelationship between successional processes and other community attributes associated with stability, diversity, dominance, and resilience. In particular, more information is needed about the biological processes associated with truncated succession, and its associated characteristics.

(ii) A 'Practitioner's Manual' should be prepared which outlines the techniques available for modelling successional processes, the data requirements and limitations of each of the major techniques, and methods of applying these to both ecological processes and to questions of management of near-natural communities.

Specific studies of selected ecosystems should be conducted with a view to providing the data necessary for the construction of comprehensive ecological and management models. Ideally, these studies should be conducted on sites where most of the key ingredients for model construction are already available. In this regard, knowledge of the effects of specific perturbations is an important factor. Because of the widespread occurrence of fire in nature, its importance as a natural and induced source of perturbation and its use in management, an in-depth study of the role of fire in ecological systems warrants high priority in future programmes.

2. Irrigation and Drainage of Arid Lands

In contrast to the slow succession of plant and animal populations in managed natural systems, the transformations brought about by irrigation and drainage in arid lands are abrupt and sweeping. On the whole, they are better understood than the dynamic effects of perturbations in grass and forest lands. Nevertheless, the translation into practical action of scientific knowledge of water use efficiency and of biological and hydrological processes in irrigated soils lags far behind research findings. Because of the vital part played by irrigation in providing the world's food supply, it is a matter of urgency that the growing knowledge of these transformations and of their impacts upon other resource use and upon human health and welfare be applied promptly and widely.

Like the analysis of successional changes, the scientific management of irrigated lands calls for close collaboration between research workers and decision-makers. It also requires a degree of integration among scientists of many disciplines – agronomy, ecology, genetics, geography, geology, hydrology, public health, and engineering – that rarely is attained.

These problems, which are recognized as of major importance under the MAB programme, led to the convening of a symposium in Alexandria in February 1976 under the auspices of the Scientific Committee on Water Research (COWAR) in collaboration with the United Nations Environment Programme (UNEP) and the Egyptian Academy of Scientific Research and Technology. SCOPE joined with MAB and COWAR in organizing a joint working group which analysed the evidence presented and prepared a report (see Chapter 5 and Appendix C) from which a summary is presented here.

a. Irrigation and World Food

In the face of a consensus that supplying food for a prospective population will require by 1985 an increase in cereals production alone of at least 30 percent over

1970, major revisions in systems for food production, storage, transport, distribution, and consumption are a necessity. Production improvement can be achieved by increasing yields on existing lands or by expanding the total area of land. Both approaches probably must be adopted simultaneously. Recent experience with the 'green revolution' provides startling examples of the need for an integrated approach in order to achieve substantial yield increases: new seed and old production practices usually result in failure. New seed requires modified planting procedures, proper fertilization, improved irrigation, and new pest control practices as well as changes in harvesting and storage procedures and facilities.

Irrigation is one means of improving the total volume or reliability of agricultural production by managing water. Water control is of significance in effecting the returns from additional inputs of fertilizers, seed, diversification, mechanization, and other management efforts. In Asia, for example, water control, linked with other inputs, may account for a fivefold difference in the yields of rice per hectare. This excludes the volume of rice yield that may be obtained where fully effective practices are employed in a farm demonstration plot or research station. It is common, in India as well as in Pakistan, to find that while the average yield for rice may be of the order of 1.6 tons per hectare, yields twice that amount will be obtained in farm demonstration plots, and research stations may report three to six times that volume.

It is estimated that about 13 percent of the world's arable lands are irrigated, and that they use about 1.4×10^{12} cubic meters of water per year. The irrigated harvested area in developing countries is estimated to increase at about 2.9 percent per year while nonirrigated arable land has been increasing at a rate of only 0.7 percent per year (Holy 1971). To the extent that food problems are to be met by enlarged production the enhancement of irrigation is important. As a minimum it is essential to maintain the present productivity of irrigated land.

b. Physical Water Efficiency in Crop Production

It is evident that irrigated agriculture in combination with other inputs can show enormous increases in crop yields. The improvement of such practices on existing land is more attractive than the irrigation of additional land because the maintenance and improvement of existing projects is less than one third the cost of bringing new land into cultivation. The possible significance of such improvements is suggested by the estimate that if, for irrigated cereal crops on approximately 70 million hectares, an average increase of only one ton per hectare per year were achieved by improved methods, it would mean an increased production of 70 million tons or nearly 20 percent of the total estimated annual cereal output of the developing countries.

It is estimated that about 80 percent of the water consumed by man is for crop production. There is a limit to potential supplies. Of the total volume of water on the earth's crust about 95.5 percent is saline water in the oceans and another 2.2 percent is imprisoned in the ice caps and glaciers. For all practical purposes the volume of water annually available for use is provided by precipitation on the earth's surface and only about 1 percent of the total supplies of the freshwater in the hydrosphere can be marshalled economically for man's activity. Irrigation diverts water from surface or ground supplies to soils where moisture is deficient for crop growth.

The physical crop producing efficiency of water is normally expressed as the ratio between the quantity of water effectively used by the plants in crop production or lost in soil leaching and the total quantity of water supplied from the source.

It may be thought of as r = yield/water taken from the source in which r is the physical efficiency. The economic efficiency of the water as gauged by its incremental value in relation to incremental cost is another measure. In fact physical efficiency ratio should be divided into two parts, r_1 and r_2, with:

$$r = r_1 \times r_2 : r_1 = \frac{\text{yield}}{\text{water retained in the unsaturated root zone}}$$

$$r_2 = \frac{\text{water retained in the root zone}}{\text{water taken from the source}}$$

It is customary to estimate the physical efficiency of water use in terms of a total project, the distribution of water to fields, or the efficiency on an individual farm. Physical efficiencies commonly range from 25 to 50 percent (Figure 13). To

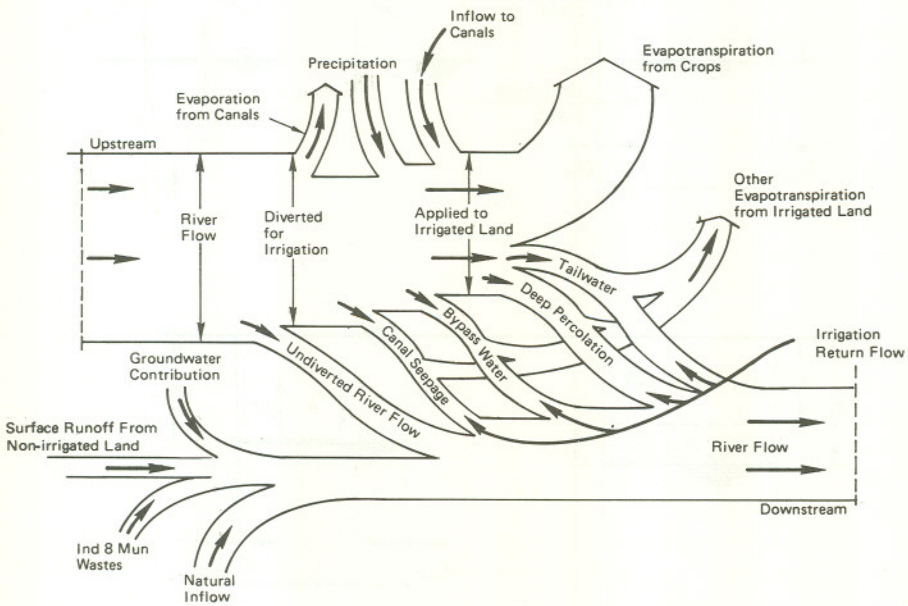

Figure 13 Model of the irrigation return flow system. Source: Hotes and Pearson (1976) (Alexandria Symposium)

understand losses that are reflected in these ratios it is essential to trace out the processes at work in distribution of water and its use by plants in the unsaturated zone (Figure 14) and to appraise what effective and economic measures can minimize them. The amount of irrigation application (J_s) which is not consumed by evaporation (E_s) or plant transpiration (T_s) moves to the saturated zone (J_w) where it moves laterally (O), accumulates causing the water table to rise, or contributes to later evaporation (E_g) and transportation (T_g). The movements are influenced by water application, soil texture, ground water storage, crop, and cropping practice.

Some of the means available for reducing water losses include controlling water flow by storage, reduction of evaporation, improvements in conveyance systems, changes in distribution systems, refinement of field application methods, selection of crops, and breeding of crops for characteristics suited to water conservation. Many limiting factors may arise in cropping, and it is known the response of a crop to water supply depends upon its stage of growth.

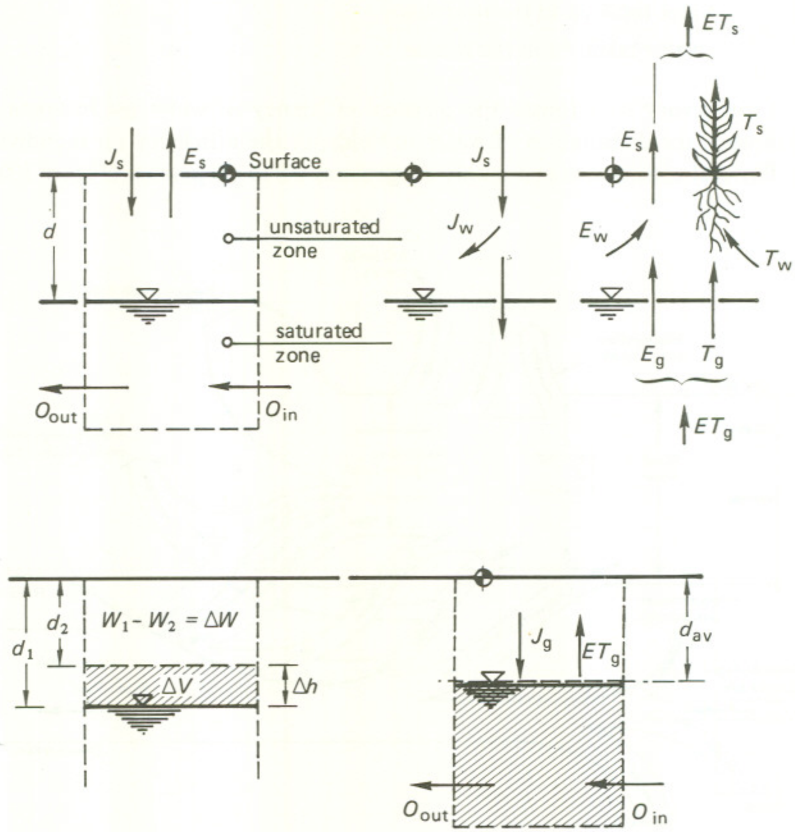

Figure 14 Distribution and movement of water in the ground. Source: Peczely (1976)

c. Water and Salt Balance in the Root Zone

The ultimate goal of water control is to regulate the moisture content of the unsaturated root zone according to the requirement of the crop. The unsaturated zone is, however, a key part of the hydrologic cycle. It is in that thin area between soil surface and the top of the saturated ground water area that water seeps down to the ground water table, moves back into the atmosphere through evaporation or transpiration by plants, or moves laterally into adjoining areas. As a result of changes in the movement of the moisture in the root zone microclimate may be altered, surface runoff may be changed, ground water regime may be modified, and the quality of water in the zone and in associated ground water storage may be changed.

Fundamental to the use of water by plants is the migration of salts in the soil. Where the water table is below a critical level the resultant vertical movement of capillary water in the layers overlying the water table is directed downwards. Infiltrating precipitation leaches as soluble salts flow from the upper levels. Evaporation of ground water rising by capillarity brings soluble salts back toward the soil surface.

A number of water-salt balance equations have been proposed by different authors. One of the simplest forms of the equation for inflow and outflow of salt is the following (Kovda 1976):

$$YC + Q_1C_1 = Q_2C_2 + Q_{dr}C_{dr}$$

Y – amount of irrigation water inflow during a given time period,

C – concentration of salts in irrigation water during a given time period,

Q_1 & Q_2 – natural flow rate of the incoming and outflowing ground water respectively,

C_1 & C_2 – concentration of salts of the incoming and outflowing ground water respectively,

Q_{dr} – the flow rate of the outflowing drainage water,

C_{dr} – the weighted average of the actual salinity of the drainage water.

Basic concepts of soil water-salt balance have been developed to show the sources, distribution, chemical composition, and total amounts of various salts as well as the dynamics of salinization in the soil and in the water used for irrigation and ground water within the irrigated area. This makes it possible to estimate possible changes in the water-salt balance in the area from the beginning of irrigation through the various stages of continued operations, and to determine the point at which a steady water-salt balance is established. It is also practicable to estimate optimum salt concentrations, the optimal and critical depth of the water table, and the most effective irrigation and leaching regimes where the latter is required (Kovda 1976). The main factor in the regulation of salt balance is effective drainage of saline ground water.

The physiological toxic limit of salt concentrations of water in the root zone lies near 10 to 12 grams/liter if the salt composition is chloride sulphate. Water with mineralization of up to 2 to 3 and even 5 to 7 grams/liter can be used for irrigation under favourable drainage conditions. However, the increase of salt concentration in irrigation drainage water will lead to a drastic increase of the drainage water outflow from the irrigation system, Several factors must be taken into account when judging the safe quality of irrigation water: nature and amount of salts in water, nature and texture of the soil, conditions of natural and artificial drainage, depths of the ground water, and the characteristic of the water-salt balance.

Land under irrigation may deteriorate through a rise in the ground waters causing water logging, through salinization (whether due to high salinity of the ground water or the dissolving of salts in the root zone by the rising ground water), and alkalinization. Especially difficult problems arise in the case of secondary soda salinization (alkalinization). The mechanisms of oversaturation of plant organs by nonorganic toxic salts are not fully understood, but it is clear that there is no direct relationship between absorption intensity of water and salts by plants, that the intensity of salt absorption is regulated by tissue permeability, and that plant metabolism has an effect on salt absorption.

It is possible to cope with soil deterioration through increasing the efficiency of the irrigation network, reducing infiltration loss in irrigation canals, construction of drainage or pumps in order to maintain deep ground waters, deep horizontal drainage, leaching waterings, and well-equipped water distribution systems. Principal ways of dealing with soda salinization include limitation of water supply, improved efficiency of irrigation systems, and removal of alkaline ground waters by drainage. Soil alkalinization can be ameliorated by gypsum or sulphur application. The proper balance of these various measures in any area depends upon the local circumstances. There rarely is a single solution: the suitable mix of action must be adjusted to physical, biological, economic and social constraints.

Semi-arid areas also require a very careful control of water application to prevent either salinization or wasteful use of water. Under present day conditions irrigation water is supplied mainly through piped networks. Water rations must be carefully linked to conditions of local climate and soil and to the specific crops grown to assure a complete uptake of the water applied by the crop without excess water remaining in the soil. To achieve maximum efficiency in water utilization by minimizing evaporation losses, modern techniques of trickle irrigation may be preferable in some situations to sprinklers or irrigation canals. The higher investment for initial installation is quickly regained by economy in water use.

It is estimated that every year several hundred thousand hectares of irrigated land fall out of cultivation as a result of salinization (Kovda 1976). FAO data suggests that no less than one-half of the irrigated area of the world is subject to salinization and is experiencing reduction in crop production as a consequence. In the Eastern Mediterranean region the percentage of salt-affected or water-logged soils amounts to about 50 percent of the total irrigated area in Iraq, 23 percent in Pakistan, 50 percent in Syria, 30 percent in Egypt, 15 per cent in Iran, and about 80 percent in Punjabi sections in Pakistan.

Although increasing salinity in irrigated soils is virtually a world-wide phenomenon, there are successful examples of preventing soil deterioration and of actual improvement of originally saline lands (Dukhovny 1975). No accurate balance has been drawn for the world as a whole, but the rate of deterioration is known to be relatively rapid and widespread. In some areas land abandonment equals the rate at which new land is brought under cultivation.

The direct result of the prevailing methods of irrigation and drainage design and operation in many areas is to so alter the water-salt balance in unsaturated zones of the soil as to impair crop production. In some places this is a long, slow process of decades, in others it may begin in a few years, especially if inadequate provision was made for drainage.

d. Other Impacts

In addition to its effects on immediate crop-producing capacity of the land, irrigation is part of a complex of practices comprising management of available water resources, controlled distribution of water over cultivated lands, and withdrawal of excessive water through drainage. Both the quantity and quality of downstream flows are affected. Ecological consequences of this complex include creation of new ecological systems related to water bodies, and radical modification of the terrestrial habitat. Some of the ecological changes are from ephemeral to perennial situations, as in the case of water bodies which formerly were ephemeral features following cloud burst rainfall and are converted into man-made lakes, irrigation drainage ditches, and the like.

Other ecological changes are related to intensive management. The subhumid and arid ecosystems are inherently unstable and exhibit potential for dramatic changes triggered by a sudden appearance of extensive areas of irrigated crops. These foster outbreaks in insect or bird population, and in flora. Arid ecosystems have limited capacity to assimilate, withstand, and respond to inputs of water, chemicals, and energy that are associated with intensive management of irrigation farms. These lead to alterations in species diversity, numbers of organisms, and the stability of their interrelationships. Aquatic organisms are most affected, but the adjoining terrestrial ecosystems may be profoundly influenced by changes in soil fauna, soil microflora, animal life, and weed flora and by the stimulation of new modes of land use in the agro-rural complex. The new agroecosystem initiates a series of secondary successional changes. Gradual buildups or sudden outbreaks of weeds or animal pests may occur as a result of species attributes and interaction.

The modification of aquatic ecosystems through irrigation practices results in a shift in humidity and sedimentation, in nutrient concentration and transport and resultant eutrophication of fresh waters, in wide distribution of pesticides and herbicides, in dissemination of aquatic weeds and phreatophytic plants, and in bacterial and viral contamination and spread of parasite vectors. It is now well established that although irrigation may have a long series of beneficial effects upon human health by improving nutrition, establishing adequate water supply and waste disposal facilities, and organizing more suitable community facilities, it also has deleterious effects through chemical pollution and through the distribution of diseases such as malaria and schistosomiasis.

e. *Conclusions and Recommendations*

As human interventions in arid land ecosystems become more widespread and complex the need increases to understand the physical, biological, and social processes which they trigger or interrupt. In a broad sense any research which increases understanding of these processes will increase the capacity of people on the land to deal more effectively with possible environmental effects from irrigation and drainage. Nothing short of a long-term programme on an international scale will bring answers to a whole array of questions which have been identified. However, the most urgent need is for the integration of investigations which have been completed or are underway or in prospect. For example, the vital question of how the occurrence of schistosomiasis among irrigation farmers may be reduced requires an interrelation of studies of disease transmission; of ways in which snail distribution may be affected by canal maintenance, wheat growth, and molluscicides; of the practicability of changing canal design and water distribution schedules; of alternative patterns of settlements and field cultivation practices; and of circumstances in which farmers may be expected to revise crop cultivation, domestic water use, bathing, and other practices.

The application of information on problems known to exist in irrigated projects may be expected to continue as in the past, at a rather slow pace and in piecemeal fashion, unless special measures are taken to speed up the process. The most direct and simple means of getting at the suitability of the planning of new or improved irrigation projects is for the principal agencies engaged in funding such activities to insist upon careful consideration of a few criteria derived from scientific appraisal of the processes involved before going ahead with either new or existing projects. To greater or less degree these criteria are embraced by current review procedures by government agencies. Nevertheless, the prevalence of projects which fall short of taking them fully into account testifies to the timeliness of stressing them now.

The questions which it would be essential to answer for any proposed irrigation venture, in addition to the economic questions of prospective costs and benefits, are: (1) has adequate provision been made for drainage and leaching so as to permanently maintain the quality of soil and water in the root zone; (2) has the full range of alternative measures for achieving efficiency in water use been appraised; (3) has the project study examined the probable effects upon aquatic and adjoining terrestrial ecosystems of changing the hydrological and soil regime in the area; and (4) has the study canvassed and assigned costs to the social and economic measures which would be required to assure that anticipated benefits from crop growth and social stability are realized? Each of these must be addressed to the peculiar conditions of the land area involved.

Where irrigation already is operating, it may not be practicable to await the result of study within a project area before acting to curb deterioration. The project manager may be obliged to take one or more courses of action on a frankly trial basis. It would help assess what is happening to world resources of land and water in irrigation projects if, as a minimum, projects were in future to report periodically on: (1) efficiency of water use; (2) area subject to waterlogging, salinization, and alkalinization; (3) area abandoned because of soil or water quality; and (4) population affected by selected water-borne or vectored diseases. These are simple measures which would yield a rough audit of gains and losses.

In the long term it is to be hoped that institutions responsible for education and training will adjust their programmes so as to anticipate fully these and other environmental issues. Materials made available to them as part of environmental and engineering information networks will assist. In the near future, however, the greatest need is to reach people who have it within their grasp to halt the deterioration and enhance the productivity of existing irrigation and drainage. Unlike some of the changes in forests and grasslands which can be predicted only with wide confidence bands, the deterioration and impacts of arid land irrigation can be projected with moderate precision. Most of the effects are not in dispute. Their remedy lies in applying, with sensitivity to the distinctive attributes of each area studied, the basic models of water, salt, and organic processes that are available.