SCOPE 27 - Climate Impact Assessment

19 Biosphere Models

Kates, R. W., J. H. Ausubel, and M. Berberian (eds.), 1985. Climate Impact Assessment: Studies of the Interaction of Climate and Society, ICSU/SCOPE Report No. 27, John Wiley.

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19.1 INTRODUCTION

Questions about conditions of human life in the biosphere belong to an untraditional science, global ecology. The problems of global ecology are unprecedented from a scientific point of view. At global scales, investigation of the state of the biosphere must be the basic object of the investigation of ecological processes. The homeostasis of humankind as a species is a key question for analysis.

A model described below demonstrates the possibility in principle for the joint numerical analysis of biospheric processes. It offers the possibility of coordinating information from different physical domains. It also offers a common language for contacts between researchers with different fields of interest. The ocean, land and atmosphere are selected as objects of analysis. The land is subdivided into regions, while the ocean is subdivided into aquatories, and the atmosphere is described by a point model. Climatic conditions influence various processes on land and in the oceans, and are themselves partly formed by them.

19.2 COEVOLUTION OF MAN AND THE BIOSPHERE

There is a deep interdependence of all processes taking place on Earth—geological, chemical and biological. Vernadski (1926, 1944) was among the first to show that the entire Earth, its landscapes as well as its hydrosphere and atmosphere, are indebted to living processes, to the living components of the biosphere. As the development of our planet proceeds, the role of life becomes increasingly influential in its further destiny.

In arriving at a logical completion of the evolutionary system of the biosphere, Vernadski developed the concept of the noosphere, that is, the sphere of the human mind. Gradually, man's mind creates a civilization that is able to influence the natural course of the Earth's evolution in a purposeful way. Gradually, that part of our planet which is becoming accessible to the active will of individuals is transforming itself into an organism, a system possessing its own goals together with the possibilities for achieving them. The outcome of Vernadski's teachings proved to be a conception of the integral unity of man and the biosphere and of the integral unity of man within the biosphere, according to which a natural stage in the development of the biosphere is its gradual transformation into a single element that may be described as a system possessing common developmental goals.

Uncovering mechanisms governing development, as scientists have done over the past centuries, begins to make it possible to glimpse into the future and to provide corresponding quantitative as well as qualitative estimates. It is hardly possible to overestimate the importance of this fact, for if man is able to forecast the outcome of his achievements, then he also acquires the possibility of guiding the course of events in a purposeful, goal-oriented way. And it is natural that he begin to make use of this power. But guidance has meaning only when the objectives for which particular actions are taken are clearly perceived.

It follows from Vernadski that the general objective of the development of civilization is to provide for a coevolution of man and the biosphere. The power of human civilization and its ability to influence the course of the planet's evolution is becoming so significant that, in principle, it can disrupt the condition that has already been established that we may call its equilibrium. Today, of course, man is still not able to destroy the entire biosphere. But under the influence of man the biosphere can shift to a new equilibrium mode and to conditions within which there may be no room for mankind. This is why it is important to have evaluations of alternative forms of human activity that will not disrupt the homeostasis of mankind as a species and that, instead of destroying man's joint development with the biosphere, will enhance it. These propositions serve as a point of departure for developing a scientific research program within which the conditions of man's coevolution with the biosphere can be studied from a wide diversity of points of view.

19.2.1 Style and Objectives

One of the principal difficulties with such studies is their broad systemic character. It is difficult to localize any particular object of the biosphere and study it independently. The biosphere is an integral whole, a single system possessing a high degree of mutual interdependence. For example, industrial discharges of CO_2 into the atmosphere may, after several decades, produce shifts in the behavior of the atmosphere over all the regions of the planet and changes in photosynthesis. Similarly, it is not possible to describe many processes taking place on land without considering ocean waters thousands of kilometers away. Thus, within the design of a research program, purely methodological problems will assume great importance. In what way should research on a system whose elements represent objects that are so varied in their physical content be organized? How should one cope with the fantastic dimensions of the problems that emerge? How should one create a simplified version of the models? Today we do not have sufficient experience, and its acquisition will turn out to be an important step in the realization of such a global research program.

The study of the properties of the biosphere as a single integral unit is still primitive. It is certainly insufficient for expressing any definitive opinion about the choice of strategies for the development of society. For this reason, providing for coevolution studies will require an extensive scientific program of interdisciplinary research. It will have to include the participation of specialists of the most varied professions—biologists and climatologists, physicists and economists, mathematicians and agriculturists, and more. It will also require the participation of specialists in the humanities. The manifold activity of these efforts should be united, the information should be integrated, and international programs should be established to solve particular problems. On what basis can such a unification of the efforts of researchers be achieved?

First, a common language should be created, which will enable specialists in various fields of knowledge to know about the research of their colleagues working in other areas of the same program, as well as to understand concrete objectives (and in a number of cases contents). Such a language can only be a language based on a formalized description, that is, the language of mathematical models.

Thus, we consider our first objective to be the creation of a system of models which would serve as a framework for a general scheme of concrete research, a basis for the planning and management of international research programs directed towards the elaboration of strategies providing for the coevolution of mankind and the environment. This system of models should be created in a form for use in a conversational 'man-machine' mode. We consider one of the results of our activities to be the fact that the still primitive system of models that has been developed until now has already helped us in our contacts with specialists in the fields of biology, soil science and other areas. The creation of an informational base has, in essence, turned into a discussion of plans for joint work.

To summarize, the present stage of the history of the civilization of *Homo sapiens*, in our view, requires the intervention of the human intellect in the formulation of principles for its further development. But this intervention may be justified only if a new scientific discipline emerges, that is, the dynamics of the noosphere, the study of the conditions of coevolution. It is the elaboration of the initial positions for the creation of the instruments of this discipline that is the principal objective of the efforts that we have undertaken.

19.3 GENERAL DESCRIPTION OF THE MODEL

Studies connected with the construction of a system of mathematical models simulating the functioning of the biosphere are being developed in three directions: simulation of processes of climate, of the biota, and of human activity. These studies are, to some extent, carried out independently. The organization of such studies is conditioned by the difficulties of complex investigation and by the necessity to refine some principles and to understand special features and methods of description. Simultaneously, it generates certain duplication. For example, a description of geochemical cycles is impossible without taking into account their impact on the climate, while a description of human activity must be connected to the conditions of environmental evolution. Therefore, one has to introduce deliberately some simplifications, parametrization of large blocks by hypothetical relationships that should be specified later when developing other studies. Each of the three main directions has the possibility of being pursued independently. We call our current descriptions, or models of the blocks, study training versions, as they are used today mainly for training the investigators themselves.

The principal obstacle that has been encountered is the poor state of knowledge concerning the principles that govern ecological and climatic processes, and the insufficiency of information concerning corresponding relationships. It is therefore important to consider not only the variability of model parameters, but also, in some cases, the possibility of representing the dynamic processes themselves in alternative ways.

Biogeocenosi are the biosphere's elementary units. Because the biosphere is made up of interacting blocks, each of which may be represented in varying degrees of detail and may embody varying degrees of autonomy, it is possible to increase the level of detail within individual blocks without interfering with others and without altering the overall model structure.

Time horizon extends to decades and centuries. These are the characteristic time spans of man–environment interactions. We do not consider processes lasting millions of years (the duration of geological ages), for it is unlikely that the formation of mountains or the accumulation of mineral resources will produce substantial changes during the time intervals that are being considered. Similarly, processes lasting less than one year are omitted. By accepting average yearly values of changes as our measure of precision, we also select one year as the time-step to employ in simulation experiments.

The following spatial blocks are distinguished within the biosphere: the atmosphere, the ocean, and regions within the land mass. The land mass is subdivided into regions that may be related to natural, economic or political boundaries. The atmosphere and the ocean are common to all. Because mixing processes in the atmosphere and in the surface layers of the ocean are rapid, no problems result from such an assumption. (The characteristic time of mixing processes in the atmosphere is of the order of several months.)

The state of each block (see Figure 19.1) is defined by a set of variables that jointly constitute a vector of major state variables. The selected variables have been well studied in aggregated form; we know their qualitative and sometimes also their quantitative relations. However, we are in an early stage of synthesis of available information that reflects the structure of both internal and external biogeochemical, ecological, social and economic relations. We have sought to make full use of information available in the literature on biospheric processes and their qualitative characteristics.

The model itself is formalized as a Cauchy problem for a system of ordinary nonlinear differential equations designed to reflect all major relations between components of the biospheric regions under consideration. It is programmed in FORTRAN-IV and is employed as a learning program at the Computing Center of the USSR Academy of Sciences and at Moscow University. The model contains more than 400 coefficients requiring quantitative data and approximately 200 relations requiring mathematical descriptions. Table 19.1 contains a list of model parameters that are common to all blocks. Quantitative values used in the model are not shown, but have been established from numerous sources (Kovda, 1975; Singer, 1975; Krapivin *et al.,* 1982). A more detailed description of the model is contained in Moisseiev *et al.* (1978).

19.3.1 The Atmosphere Block

The basis for the atmosphere block is given by a description of the flux of solar radiation. The atmosphere regulates the flux, secures the stability of the radiation balance, and creates necessary conditions for life on our planet.

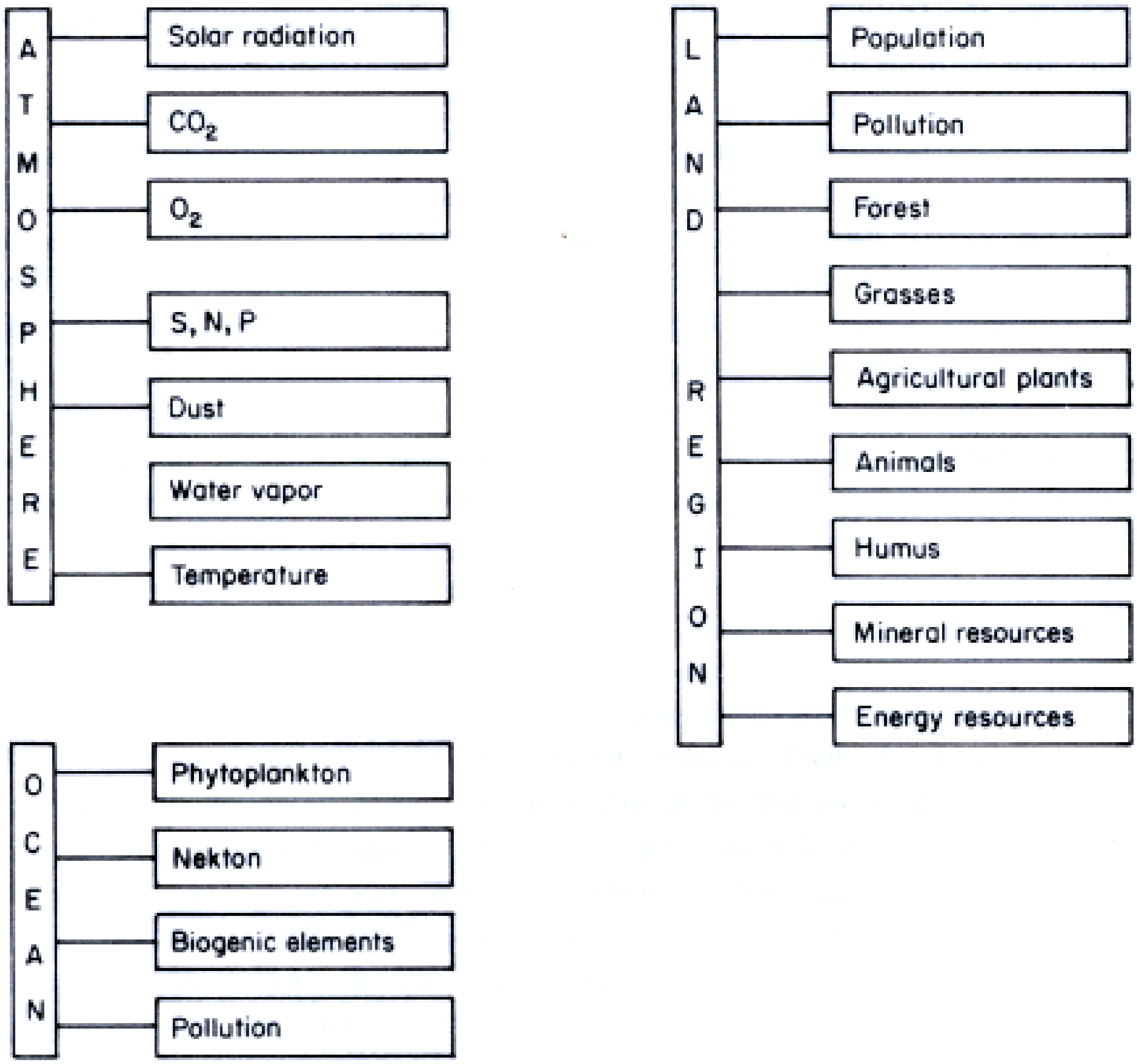


Figure 19.1 Spatial blocks within the biosphere and the variables

The upper layers of the atmosphere receive radiation from the sun, evaluated on the average by $E_o(t)$ = 1.94 cal cm^{-2} min^{-1}. The atmosphere reduces this flux, partially absorbing and reflecting it. Analysis of experimental data allows the following approximation for description of this process: $E(t) = E_o(t)\exp(-\alpha B(t) - \beta)$, where α is the coefficient of the solar energy absorption by the atmosphere due to dust and cloudiness, β is the transparency index of the clear atmosphere, and B is the measure of atmospheric dust. According to available climatological data we take α=0.144, β=0.477.

Propagation of solar radiation energy through the ocean depends on water transparency and can be described by the following relation: $E(z,t) = E(t)\exp(-\alpha_1 z)$, where z is the depth (in meters) and α_1 is the vertical radiation reduction, α_1 being an integral characteristic of water quality.

A great influence on the general radiation balance of the Earth is exerted by its surface albedo. The albedo depends on the state of the land and ocean—area of vegetative cover and urbanized surface, and roughness of ocean surface, for example. In a strict formulation, albedo should be a function of state variables of a model, but we initially consider it as a constant, assuming that its changes during the time periods under consideration are negligible.

Table 19.1 Selected model parameters

1.	Area of biosphere: land, ocean, forests, arable land, land under cultivation, land under human structures
2.	Level of solar radiance at Earth's surface at which glaciation may occur
3.	Efficiency of solar energy utilization: in the biosphere, on land, in oceans
4.	Albedo of the Earth–atmosphere system
5.	Total mass of atmosphere
6.	Average temperature of atmosphere at Earth's surface
7.	Volume of dust in atmosphere
8.	Volume of dust entering the atmosphere
9.	Biomass of the biosphere: land, forests, nekton
10.	Humus in soil
11.	Net primary production of biosphere: on land, in the ocean
12.	Consumption of primary products: by nekton, by animals, by human population

13. Volume of food products extracted by man: on land, in the ocean

14. Volume of nekton catch

15. Reserves of animal food

16. Global reserves of coal

17. Energy consumption per capita in Europe

18. Rate of annual increase in average per capita energy consumption

19. Rate of increase of consumption of nonrenewable resources

20. Volume of industrial wastes released into the atmosphere

21. Volume of pollutants entering the ocean

22. Population growth in 1970: birth rate, death rate

Based on published accounts (Kovda,1975; Singer, 1975; Krapivin *et al.*, 1982)

Changes in the amount and distribution of biota alter the cycling of carbon and can generate climatic changes that, in their turn, can influence biotic processes. The current state of climate research does not allow accurate prediction of regional climatic changes due to anthropogenic influences. Therefore, we consider the part of the model that simulates the climate as a point model, that is, the state of the atmosphere is described by values of solar radiation energy, by the general amount of CO_2 and other constituents of the atmosphere, and by the mean global atmosphere temperature near the Earth's surface. Such a choice of variables allows us to take into account, more or less exactly, the influence of human activity on the climate of the planet and of climatic factors on biological processes of the land and ocean.

The sensitivity of atmospheric temperature to changing CO_2 content has been calculated (Krapivin *et al.*, 1982); the results are generally consistent. For this model the relation is taken in accord with the calculations of Rakipova and Vishnyakova (1973). The influence of changing temperature on the moisture and precipitation regime has not yet been included.

Among anthropogenic factors, there are several that might impact on climate. These include the burning of fossil fuels and changing land use, which release CO_2; other industrial and agricultural activities that may release `greenhouse' gases; industrial activity that results in increasing aerosol release into the atmosphere and disturbs the thermal regime of the planet; and power plants that excrete a great amount of heat (10^{20} Jy^{-1}).

The presence of oxygen in the atmosphere defines many metabolic processes. Although according to current evaluations the amount of oxygen in the biosphere is stable, the model takes into account the actual regimes of oxygen exchange between different biosphere components and regions, as well as the possibility of equilibrium disturbances (see Table 19.2).

Table 19.2 Selected parameters of the oxygen cycle

Content of O_2 in the atmosphere by volume, weight
Volume of O_2 released through photosynthesis: land plants (including forests),
aquatic plants
Volume of O_2 consumed each year on burning fuel
Yearly loss of O_2
O_2 required to oxidize 1 mg of petroleum
Reduction in coefficient of exchange of O_2 between water and the atmosphere
in the presence of a 40-μm layer of petroleum

One of the most intensive and important biospheric processes is the circulation of carbon. The presence of carbon in the atmosphere, mainly in the form of CO_2, defines to a considerable extent the climate of the planet. The climatic conditions and amount of CO_2 in the atmosphere at any given time are, in their turn, factors on which depend the intensity of both the atmospheric CO_2 assimilation by plants and its release into the atmosphere, resulting from decomposition of dead organic matter in the soil. The CO_2 content in the atmosphere is defined by the balance between these two processes, as well as processes in the oceans. It is also necessary to take into acount CO_2 release due to volcanic activity and the influence of anthropogenic factors.

When coal, oil, gas or wood burn, CO_2 is released into the atmosphere (during one year an amount at present equal to about 0.7 percent of the amount of atmospheric CO_2, or about 10 percent of the CO_2 assimilated for construction of plant biomass). Destruction of forests and reduction of other areas covered by vegetation increase the scale of anthropogenic influence on the cycle of CO_2. The gas exchange between the atmosphere and the ocean is described by Machta's (1971) model, and the land-atmospheric exchange by Tarko's (1977) model. Some characteristics of global carbon processes are given in Table 19.3. In addition to carbon, the representations are derived from available literature (Krapivin *et al.*, 1982) about the nitrogen, sulphur and phosphorus cycles in the biosphere using rather simplified schemes of their circulation.

Table 19.3 Selected parameters of the carbon dioxide cycle

Concentration of CO_2 in the atmosphere in 1970
Mass of CO_2 in the atmosphere
Assimilation of CO_2: by land plants, by phytoplankton
Average yearly addition of CO_2 (1962–65, 1970–71) through burning of fossil fuels
Rate of production of CO_2 by human population
Rate of addition of CO_2 from the Earth's core (volcanic CO_2)
Rate of addition of CO_2 from humus decomposition and respiration
Mass of CO_2 dissolved in the hydrosphere
Volume of CO_2 contributed by a person or animal through respiration
Optimal concentration of CO_2 for respiration and photosynthesis

The atmosphere also contains water in a gaseous state, and the character of the water cycle is determined by many biospheric processes. The relative content of water in the atmosphere is not large, but it is of great importance as one of the basic factors of atmospheric turbidity (cloudiness), defining climate in many respects. Moreover, the productivity of plants depends substantially on rates and distribution of precipitation and humidity.

In the model under consideration we have accepted a simplified scheme of the water cycle, taking into account water vapor fluxes between land regions and between land and ocean; atmospheric precipitation; evaporation from the ocean and land surfaces; and the transpiration of plants.

19.3.2 The Ocean Block

Like the atmosphere block, the ocean block is represented by a point model, that is, a model with ideal mixing. It contains the following variables: contents of phytoplankton, zooplankton, nekton, and biogenic nutrient elements; the extent of ocean pollution; and CO_2 content in the upper mixed layer and in the deep ocean.

The importance of the ocean in determining the composition of the atmosphere is also taken into account in the model, mainly in the exchange of CO_2. The exchange of CO_2 between the atmosphere and the ocean depends to a large degree on the temperature of the atmosphere and on the CO_2 content in the air, which has been increasing during recent years. In other words, the CO_2 exchange depends directly on human activities.

While the ocean is of great importance as a food source for man, it contributes only about 1 percent (energy equivalent) of the total gross production of food (Vinogradov and Monin,1976). Biospheric processes in the ocean are described by equations obtained by Vinogradov *et al.* (1975). Fishing is defined by the catch strategy chosen by a land region. Effects on reproduction of fish resources are not included. Photosynthesis is the main source of organic matter in the ocean. Photosynthetic rate is partly a function of light intensity and decreases with deviation of light intensity from an optimum value. Photosynthesis also depends on temperature, concentration of nutrient and other elements, phytoplankton biomass, and other parameters. Equations for phytoplankton behavior can be derived by using the various phenomenological relations.

We assume that Liebig's law of limiting factors is correct (Taylor, 1934). According to Liebig's law, the photosynthetic rate at each moment depends only on one factor, although the factors themselves can change in the process of system development.

The model includes vertical cycling of biogenic nutrient elements. It is assumed that biogenic element reserves are not limited in deep ocean layers (deeper than 200 meters), so that they can limit photosynthesis only in upper layers. Biogenic elements are taken out of the upper layer partly through the sinking of feces and dead organic matter. The assimilation rate of biogenic elements by phytoplankton is proportional to the photosynthetic intensity.

The rate of change of the nekton biomass is regulated by the temperature of the environment, by the character and intensity of trophic relations (ratios), by natural mortality, by mortality due to pollution, and by mortality due to population exploitation (fishing).

The introduction of a generalized element like nekton into the model is only a rough approximation for the real structure of the system. However, the approximation seems to be satisfactory for the initial version of the model, since nekton is the highest level in the trophic pyramid in the ocean ecosystem and its energy content is rather small in comparison with the other levels. Accuracy of the nekton description influences the global element and energy cycles only to a small extent. On the other hand, nekton is a human food resource, and further detail in its description will be necessary for a more refined representation of the structure of food relations in the dynamics of human populations.

19.3.3 Land Regions

Land vegetation is characterized by a large variety of species and by wide ranges of productivity and rates of exchange with other media. The gross primary production of land varies from 28,140 kcal m^{-2} y^{-1} in tropical woods to 489 kcal m^{-2} y^{-1} in a desert. The concept of a land region is introduced in the model to take into account all the variety of vegetation forms and to keep the point character of the model blocks. It allows an approximate account of the zonal character of the Earth's vegetation without introducing space coordinates. The model involves three types of vegetation: woods, agricultural plants and natural grass vegetation.

Change in biomass for each type of vegetation is described by a first-order differential equation in which the photosynthetic rate is a complex function of light intensity, humidity, humus state, the amount of fertilizers put into the soil, the composition of the atmosphere, and so forth. The rate of decay of plants is also taken into account, as well as consumption of plant biomass by animals and people.

Photosynthetic production is consumed by the animals of the Earth. They are treated in the model as a single-state variable of the biosphere. The variable is characterized by average growth and death rates. Animal bioproduction is in turn consumed by man.

Soil-forming processes are of great importance in the global element and energy cycles. The numerous stages of soil humus formation, which is the last link in a chain of biogeochemical organic matter transformations, are described by one component — `humus'.

There are several estimates of the amount of humus in the biosphere (Kovda, 1975), but the estimates do not differ much. An average estimate equal to $2.3 \cdot 10^{12}$ tons has been taken in the model. The model is not very sensitive to variation in this parameter.

It must be noticed that the humus is important for the composition of the atmosphere. The model assumes that the rate of change of humus depends on the intensity of accumulation of the organic waste of plants. It is assumed that the decomposition rate is directly proportional to the mass of decomposing substance, and that it increases exponentially with temperature. It is taken into account that a considerable rise or fall in temperature depresses the activity of soil microorganisms and, hence, decreases the decomposition rate. It has also been taken into account that the humus decomposition rate decreases with deviations of humidity from some optimum value.

The description of the demographical block is the most difficult part of the simulation. While relations of cause and effect, including a mortality coefficient (more exactly, an index of mean-life duration), have been specified, there is no unique understanding of the processes describing the birth-rate dynamics in the *Homo sapiens* population. Extrapolations based upon demographical statistics are not appropriate because the evolution of the global system is computed for many decades ahead, and previous demographic experience shows how rapidly and inexplicably basic demographic parameters can change. Thus, the demographic dependences accepted in the model are hypothetical to some extent. The model representation is, however, more sophisticated than a simple model of exponential growth. Parameters are verified by demographic data and, in contrast with some other models, they allow for inverse cause-effect relationships.

19.3.4 Human Activities

It is only in recent years that man has begun to play one of the leading roles in the biosphere. And while until recently it was possible to speak of evolution of man as an *element* of the biosphere, his increasing independence from the biotic environment creates a `technological' environment for his existence. Also the increasing load on the biosphere, as well as the comparable roles of anthropogenic and biogenic cycles of matter and energy, make it now appropriate to refer to the *joint* evolution (coevolution) of the biosphere and of *Homo sapiens*.

Let us consider some figures. During the last 30 years man has consumed as much mineral raw material as during his entire preceding history. Between 1950 and the early 1970s, the production of energy per capita was growing exponentially, with an average yearly increment of 4–5 percent. Man retrieves from ocean and land ecosystems $17 \cdot 10^6$ tons per year and $1.3 \cdot 10^9$ tons per year, respectively, of food products. And while the biosphere still possesses a certain reserve for increasing the productivity of its ecosystems, the current level of their exploitation is already quite intense. It is in order to reflect these processes that other blocks representing human activities besides the `population' block are included, namely pollution generation and energy production.

Anthropogenic influences on the environment are quite diverse. It was already noted in describing the atmosphere block that corresponding releases of CO_2 and aerosols into the atmosphere influence the planet's thermal regime. But the influence of human activities is not limited to the atmosphere. Changes in the overall carbon dioxide cycle also influence humus formation. Another major anthropogenic influence relates to the depletion of easily accessible mineral resources. The influence of changes in the environment on human activities is equally diverse.

All of these factors are parametrized within the model by defining the following hypothetical time relations:

1. the rate of generation of pollution per capita (this is a characteristic of both the standard of life and the technology of social production);
2. an indicator of the rate of dissipation of pollution;
3. the intensity of mineral source utilization;
4. indicators of the rate at which available arable land is brought into the agricultural sphere and of the growing productivity of agricultural ecosystems;
5. the share of capital investment in agricultural development, the replenishment of resources, the development of new types of resources, and antipollution measures.

The human activities block embodies possibilities for changing over time the coefficients of mutual exchanges in resources and food among regions of the land mass, as well as for specifying similar changes in other parameters.

The large volumes of matter and energy that circulate in the biosphere are accompanied by releases of large quantities of components that can be harmful to the environment. Before 1800, humans had access only to those forms of solar energy that were released in the course of various biological processes. But during the last century and a half this situation has changed fundamentally and still newer prospects have emerged during the past 20 years, following the utilization of nuclear energy. For each person living in the United States of America, 10^4 W d^{-1} are expended, and this number could continue to increase. The average per capita consumption of all types of energy in Europe is 70,000 kcal d^{-1}. The total volume of energy that is produced has doubled several times in this century in a period of 10 years or so.

The world's growing population and associated growth in energy production causes a pollution of the atmosphere, of soil, and of water. In particular it tends to increase the environment's temperature. Available estimates indicate that a total of 2.7 billion tons of coal and 1.6 billion tons of petroleum are burned on our planet each year, while 1.25 million tons of pesticides are added to the soil. Each year $1.5 \cdot 10^{10}$ tons of CO_2 are added to the atmosphere and $9 \cdot 10^9$ tons of O_2 are expended. The biosphere's declining absorption capacity causes a yearly growth in the concentration of CO_2 and a reduction in the volume of O_2.

A generalized component called `pollution' is considered in the model for purposes of simplification. It expresses only averaged characteristics of numerous types of pollutants. While this approach helps to keep the model simple, it is justified more by the absence of reliable knowledge concerning the influence of various types of pollutants on biogeocenotic processes.

Forrester's equation (1971) is employed in determining the rate of change in the concentration of pollutants in a region. It reflects increases that are proportional to population growth, as well as a coefficient dependent on time. It is assumed to increase as the material level of the population increases.

Pollutants operate as inputs in processes of natural decomposition and pollution neutralization activities. The latter proceed at a rate that is linearly dependent on the share of capital that is assigned to these purposes and is inversely proportional to the expenditures required to neutralize a unit of pollutant.

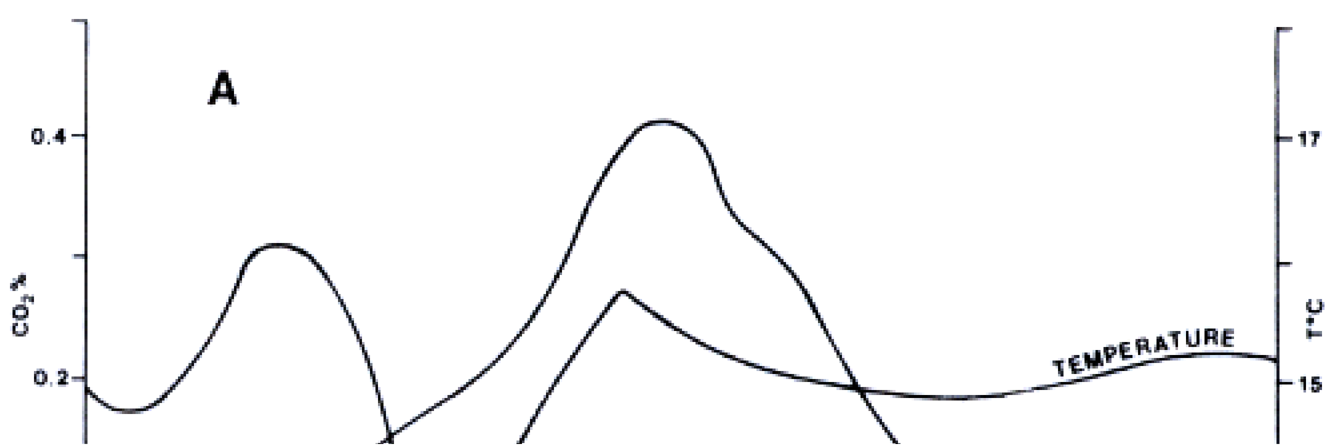
The ocean's pollution results from the total volume of all pollutants entering it from all land regions. They reduce its transparency, attenuate the growth in the biomass of its live components, and increase the coefficient of mortality.

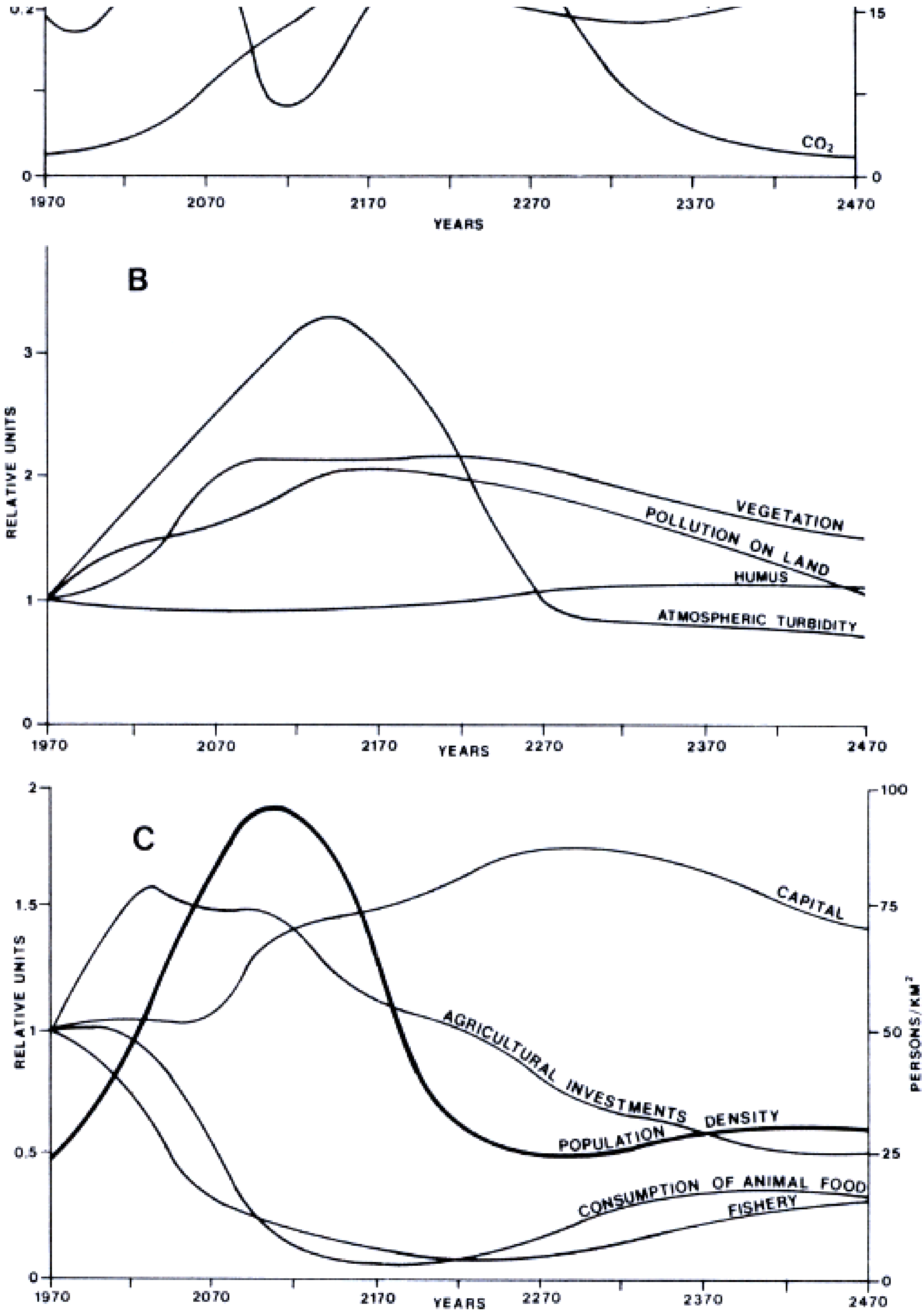
A generalized Forrester type of equation is employed in the model to describe the depletion of all non-renewable resources in the biosphere. Possible changes in the initial conditions of the corresponding differential equation may be entered either discretely or gradually. Shifts to new mineral resources are represented as changes from one set of initial conditions to a series of others at specified time intervals.

19.4 EXPERIMENTS WITH THE MODEL

Preliminary computer calculations point to the logical consistency of model behavior but also to a need for greater precision within the existing structure blocks and a need for additional blocks. Experiments with the model require the specification of various scenarios. The manner in which they must reflect alternatives in the future development of society, alternative control policies, and estimates of rates of progress in science and technology call for a separate article. At the present time we shall simply describe the findings of the main experiment that has been carried out with the model so far. It addressed the following question: how will the biosphere evolve if existing trends in anthropogenic influences and scientific and technical progress are maintained?

The results are shown in Figure 19.2. The curves of the first of these figures (19.2A) describe the dynamics of CO_2 in the atmosphere, as well as those of average global temperature. The trajectories are carried to the year 2470, that is, over a relatively prolonged period of time. While these forecasts are extremely hypothetical, they do appear to provide a certain quantitative image of possible trends in the system's evolution. In particular we see that while the average temperature fluctuates in a period of approximately 200 years, it remains within an interval between 13 and 17 °C. Let us recall that some climatologists believe that should these boundaries be exceeded, a `climatic catastrophe' could result. It is interesting that a situation arises in the experiment towards the middle of the twenty-second century that is characteristic of the distant geological past, namely, a hot climate, a high concentration of carbon dioxide gas in the atmosphere, and an intense development of plant life (see Figures 19.2A and B). This is accompanied by a sharp increase in the volume of dust, reaching four times larger than at present by the year 2125. While the behavior of dust content in atmospheric pollution is similar to that of population density (Figure 19.2C, that of land pollution is more complex. This is partly because such pollutants are more `durable', and partly because their production is closely associated with the economy. The curves in Figure 19.2C represent the behavior of population and certain economic factors. In particular it may be seen that rapid population growth causes the adequacy of food supplies to fall by nearly 50 percent. The shortage of proteins is then particularly serious. And while in terms of its caloric value the food ration does not generally meet the required minimum, its contents experience a sharp shift toward vegetable foods. The combined influence of environmental pollutants and shortage of protein in food rations causes a sharp decline in population density, which by now, the beginning of the twenty-second century, has increased by four times. Following a decline of more than 100 years it then stabilizes at its present level. By 2470 all other variables, too, generally return to their initial values (except for nonrenewable resources).

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2270
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Figure 19.2 A: Projected evolution of the atmosphere under continuation of present trends; B: Projected state of the biosphere: hot climate, high concentration of oxygen, and intense development of plant life; C: Population density, certain economic factors, and evolution of agriculture and diet under assumption of initial maintenance of current trends

The model was built for the sake of experiment, and the obtained modeling results cannot be regarded as predictions. Moreover, if for decades mankind is monitoring the early phases of changes similar to those described above, it is likely that new ideas leading to the radical reconstruction of production relations will occur.

19.5 CONCLUSION

The systems-oriented model of global biospheric processes described above is inevitably incomplete. It represents a learning model whose behavior cannot be interpreted as a reliable forecast. At the same time, it does express fundamental causal linkages in nature and is able to describe relevant interactions in relatively flexible ways. The authors are working in the direction of further sophistication and detailing of the model and its blocks. The main guidelines for this work are as follows.

1. Improvement of functional forms for different relationships between model components and more accurate determination of their coefficients.
2. Taking into account the actual spatial distribution of plant formation types within a land mass for the carbon cycle submodel. Annual primary production and the rate of dead organic matter decomposition within a given cell are proposed to be a function of annual temperature and precipitation for each cell. Tentative results are described in Bazilevitch *et al.* (1982).
3. Development of a spatial climatic model that could provide annual temperature and precipitation for defined cells.
4. Addition of blocks reflecting economic and political factors.
5. Recognition of the multiplicity of objectives and corresponding differences among various groups, countries, and regions. The biosphere encompasses regions that differ with regard to their strategies and tactics in achieving social and economic development and in exploiting resources.

Finally, it is appropriate to conclude by mentioning the problem of critical parameters. In the evolution of any complex nonlinear system, it is possible to distinguish the relatively `calm' course of the process when its parameters are not in the vicinity of their bifurcation values. In this situation a chance perturbation may disturb the state of equilibrium (to be more exact, the quasi-equilibrium) of the system only temporarily. The inner forces of damping that are inherent to nature return the system to its initial state (or else close to the initial one). It is another matter with situations that are close to the values of the `carrying capacity of the biosphere', where new states of equilibrium may emerge.

There may be many states of equilibrium, and it may be impossible to predict to what state of equilibrium a system will come—it may depend on unforeseen or chance factors. In the case of the biosphere, we do not know of any other states of equilibrium except those that are observed. For this reason the study of carrying capacities is an important problem standing before science—we do not have any guarantee that the present-day load on the biosphere is sufficiently removed from a critical one. Indeed, there is an indirect basis to suppose that a number of characteristics of the biosphere are close to their critical values. For example, an increase in the average temperature by 3 or 4 °C could lead to the beginning of an irreversible melting of glaciers. What will the properties of the new state of equilibrium of the biosphere be like; will they permit the existence of man? We do not know.

ACKNOWLEDGMENT

We have the pleasure of thanking M. I. Bazilevitch and P. I. Medow for helpful comments.

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The electronic version of this publication has been prepared at the *M S Swaminathan Research Foundation, Chennai, India.*