MODELS OF BIOSPHERE PROCESSES

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Contents

Summary

This paper presents the current state and perspective of mathematical modeling of the biosphere. One of the models which are considered in the paper is a spatial model of global carbon cycle in the atmospheric system of plants and soil. In this model biosphere dynamics under the impact of industrial CO_2 emissions, deforestation, and soil erosion is investigated. Carbon dioxide budget of the whole biosphere in 1860-1995 and budget of countries in 1995 is calculated. It is shown that delay of beginning to implement the Kyoto protocol to the UN Framework Convention on climate change for

10 years does not have a significant role. Fulfillment of the Le Chatelier principle is investigated. It is shown that if atmospheric carbon dioxide concentration is large enough it is possible that this principle will not be carried out. In this case terrestrial ecosystems will become the sink of carbon dioxide. The next model which is presented here is a spatial model of carbon and nitrogen cycle in Atmosphere - Ocean system. Spatial distribution of the seasonal fluctuations of carbon content as far as the partial pressure of carbon dioxide is estimated. Finally a model is considered for contaminant impact on ecosystems in a region. Birth and dynamics of zones of degradation for forty years were reconstructed in modeling.

1. Introduction

Now activity of mankind has resulted in a sharp global change of processes in the biosphere. The change in nature spreads over the whoe globe and is obviously irreversible in character. The pollution of three environments, air, land and water in which live matter exists, aggravates:. There is a global increase of quantity of greenhouse gases, carbon dioxide, methane, and chlorofluorocarbons (CFCs), in the atmosphere, climate warming increases, functioning of ecosystems is been broken, the landscapes head to a collapse, there is a cutting down of forests, and soil erosion.

It is clear now that if humankind does not change modern rates and technological methods of biosphere resources usage it will result in a catastrophe for humankind. The problem is to find the ecological, technological, economic, demographic preconditions for overcoming the crisis.

In the finding acceptable ways of development in harmony with nature, mathematical models are important. There are three main types of biosphere models: models of biogeochemical cycles (such as models of global carbon cycle), models of shifting the borders of plant communities (such as Holdridge life zone model), and models of contaminant impacts on ecosystems. Three modern simulating models describing dynamics of biosphere and its parts which are influenced by results of human economic activity will be presented. Two of them are models of global biogeochemical cycles and the third is model of contaminant impact on ecosystems in a region.

2. Modeling of the Global Biosphere Cycles in the Biosphere

Investigation of the global carbon cycle in the biosphere is important. On the one hand, carbon is a component of live and dead organic matter of the biosphere and hence is the indicator of ecological processes. On the other hand, it is present in the atmosphere as carbon dioxide that defines the greenhouse effect and is a factor influencing the climate of the planet. The next in importance is the nitrogen cycle.

The first mathematical model of global biogeochemical cycles is the model of V.A. Kostizin which was published in 1935. In this model the global cycle of oxygen and carbon in the system Atmosphere - Terrestrial Biota - Ocean - Crust is considered. The model represents a system of seven ordinary nonlinear differential equations and is investigated analytically.

In the system of the equations it is possible to allocate two independent subsystems. One of them represents the classical Volterra Predator-Prey system. Its analysis shows the periodic solutions with "fast" fluctuations of weight of plants and animals with a period 15-140 years. Other subsystem at the chosen parameters gives the solution of a type "steady focus" and demonstrates "long" fading fluctuations in the atmosphere - ocean system with the period of millions years. The amplitude of fluctuations is increased with amplification of volcanic activity.

It may be said that the modern models of global cycles of elements have appeared after H.E. Suess who measured the ratio of radioactive carbon C^{14} to stable C^{12} in wood rings and on this basis made a conclusion that the concentration CO_2 in the atmosphere over the last decades increased. Suess found out that the ratio of the atmospheric radioactive C^{14}, which is constantly formed in the atmosphere due to the action of space particles, to stable C^{12} is changed as a result of "dilution" of atmospheric CO_2 by a flow of CO_2 from fossil fuels which practically do not contain C^{14} (the period of the half-decay of C^{14} is equal to 5730 years).

Early models of global carbon cycle described the dynamics of both C^{12}, and C^{14}. They took into account of a very simple form (small amount of «boxes» - variables) of processes in the Atmosphere - Ocean and Atmosphere - Terrestrial Vegetation systems. In the later models the number of boxes was increased: horizontal and vertical dividing of ocean and spatial dividing of land ecosystems were taken into account. Then appeared models which took into account other biogeochemical cycles: nitrogen etc.

The majority of early models focused on calculation the forecasts of CO_2 concentration in the atmosphere. Qualitative research was carried out only in connection with the analysis of accuracy of atmospheric CO_2 and temperature forecasts. In contrast, nowadays research is directed to investigate the role of separate terrestrial ecosystems or separate regions of ocean in the absorption of CO_2. The feedback of terrestrial ecosystems changes to atmospheric CO_2 and climate change is of interest now.

Modern models are focused either on detailed description of elements of biogeochemical cycles such as increasing the spatial and/or time resolution or on investigation of new data of measurements such as investigation of fluctuations of the atmospheric CO_2 concentration.

Here we consider two global models. One of them is the spatial model of global carbon cycle in the Atmosphere - Plants - Soil (APS) system. The next is a spatial model of carbon and nitrogen cycle in the Atmosphere - Ocean (AO) system. The behavior of complete Atmosphere - Plants -Soil – Ocean system influenced by results of anthropogenic activity will also be investigated.

3. A Spatial Model of the Global Carbon Cycles in Atmosphere - Plants - Soil System

3.1 Description of the model

This model was developed by A.M. Tarko. In the APS model all land territory is divided to into cells of size 0.5x0.5^o of a geographical grid. It is supposed that in each cell there is vegetation of one type according to the chosen classification. Two kinds of classification are used: 1. N.I. Bazilevich and L.E. Rodin. 2. J.S. Olson. Processes of plant growth and death, soil forming and decomposition are taken into consideration. These processes are expressed as carbon exchange flows between atmosphere, plants, and soil in each cell of the land.

The model is described by system of ordinary nonlinear differential equations. In each cell of land with a number i ($i = 1,...,I$) the ecosystem is characterized by quantity of carbon per unit area in phytomass of living plants B_i and in humus of soil D_i. Let the area of the cell be denoted by σ_i. A time unit accepted in the model is one year.

The total quantity of carbon in the atmosphere is denoted by C. The climate in a given cell is characterized by annual surface air temperature T_i and annual precipitation P_i. The initial values of B_i, D_i, T_i, P_i and C_i will be denoted by $B_i^o, D_i^o, T_i^o, P_i^o$ and C_i^o. The values of T_i and P_i for each cell of land depend on the quantity of CO_2 in atmosphere because of the greenhouse effect and are calculated with the help of a General Circulation Model (GCM).

Let us assume that annual production of vegetation in each cell depends on the atmospheric CO_2 concentration, temperature, and precipitation in a given cell and does not depend on the ecosystem type.

The dependence of humus decomposition rate on temperature and precipitation in a given cell was also taken into account. According to the model the quantity of humus in each cell in a steady state does not depend on the ecosystem type and is a function H of T_i and P_i: $H = H(T_i, P_i)$, so that $D_i^o = H(T_i^o, P_i^o)$. The specific rate of humus decomposition h is a function of T_i and P_i: $h = h(T_i, P_i)$.

It is supposed that in the absence of anthropogenic CO_2 emissions into the atmosphere the quantity of carbon in the biosphere is constant. Prior to the beginning of anthropogenic influences the system was in a steady state (usually 1860 is accepted as the year when the industrial era began).

Three anthropogenic impacts on the biosphere resulting in CO_2 growth in atmosphere are taken into consideration. The first source is fossil fuel burning (industrial releases). Let V be industrial releases of carbon flow into the atmosphere. The second anthropogenic source of emissions is cutting down of the trees. The phytomass of trees which are cut is decomposed with some delay and its carbon in the form of CO_2 goes to the atmosphere. Let B_d be the amount of carbon in trees that are cut down. The third source is soil erosion resulting from improper land use. In the model the dead organic matter of the soil which is decomposed with some delay and its carbon as CO_2 goes into the atmosphere. Part of the decomposed carbon goes to the rivers and then to the ocean. Let D_e be the sum of carbon which was carried out because of land use.

Dynamics of carbon in a system APS is described by the following system of equations:

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\left.
\begin{aligned}
& dB_i / dt = \nu_i Q_i - m_i B_i - k_d^i B_i, \\
& dD_i / dt = \varepsilon (m_i B_i + (1-\nu_i) Q_i) - h(T_i, P_i) D_i - k_e^i D_i, \\
& dB_d / dt = \sum_{i=1}^{I} (k_d^i B_i \sigma_i) - q_d B_d, \\
& dD_e / dt = \sum_{i=1}^{I} (k_e^i D_i \sigma_i) - q_e D_e - q_m D_e, \\
& dC / dt = -\sum_{i=1}^{I} ((1-\varepsilon_i)(m_i B_i + (1-\nu_i) Q_i) - h(T_i, P_i) D_i) \sigma_i + q_d B_d + q_e D_e + V, \\
& \qquad\qquad\qquad i = 1, \ldots, I.
\end{aligned}
\right] \quad (1)
$$

Here, $m_i, \varepsilon_i, k_e^i, k_d^i, q_d, q_e, q_m$ are coefficients, $Q_i = Q(C, T_i, P_i, B_i) = Q$ is annual production of the plants per unit area.
There are two kinds of dependencies of annual production. The first dependence was developed by C.D. Keeling. In this case annual production depends on atmospheric CO_2 concentration and on plants phytomass:

$$Q = F_o (1 + \beta \ln(C / C^o))(B / B^o)^{2/3}. \quad (2)$$

Here F_o is annual production at the initial state, B is plants phytomass, expressed in carbon units, C^o, B^o are initial values of corresponding variables, and β is a coefficient.

The second kind of dependence was developed by A.M. Tarko. In this case annual production also depends on atmospheric CO_2 concentration but does not depend on plants phytomass and depends on temperature and precipitation:

$$Q = F(T, P)(1 + \frac{\delta}{10}(C / C^o - 1)). \quad (3)$$

These two kinds of dependencies define different dynamic properties of the system but in position of variables which are not far from a steady state simulating experiments show that difference is not large.

The Dependence of annual production $F(T, P)$ on temperature and precipitation, which was developed by A.M. Tarko, will be used. It expresses in a tabulated form the nonlinear dependence of annual production on temperature and precipitation.

Coefficient ν_i expresses part of annual production, which goes to trees. So flow $\nu_i Q_i$ expresses flow of carbon to the trees and $(1-\nu_i) Q_i$ is a foliage fall down. If $\nu_i = 0$, then foliage fall down is equal to annual production and in a given cell there is a grassland ecosystem so variable B_i is a quasi variable.

Let $k_d^i B_i$ be a flow of carbon of cut down plants, $k_e^i D_i$ is soil erosion. Flow $q_d B_d$ is decomposed part of trees which were cut down, flow $q_m D_e$ is decomposed part of dead organic matter which was carried out due to erosion, flow $q_o D_e$ is a flow from decomposed soil to the ocean.

3.2 Computer Realization of the Model- Pre-industrial State of the Biosphere

A computer program complex was developed to make calculations on the model. It works under the control of Windows 95/98/NT. In the case of 0.5x0.5^o resolution the number of terrestrial cells equals to about 60,000 and so about 120,000 differential equations were solved.

Validation of the model was performed according to procedure that is traditional in global CO_2 cycle models. In different simulation experiments coefficient δ was varied until the curve of atmospheric CO_2 matches the data from measurements: in 1860 (ice cores data) and in 1959-1997 (direct measurements at different CO_2 monitoring stations). In the result of identification, the chosen value of δ appeared to correspond to its values in experiments in plant laboratories.

Dividing the territory into cells 0.5x0.5^o allowed allocating all countries of the world with size larger than 50x50 km.

The computer map of annual production of the world vegetation at its pre-industrial state is shown in Figure 1. The map is based on the annual production dependence of A.M. Tarko. Comparison of observed values at different points of the Earth and calculated ones shows that their differences do not exceed the accuracy of measurements.

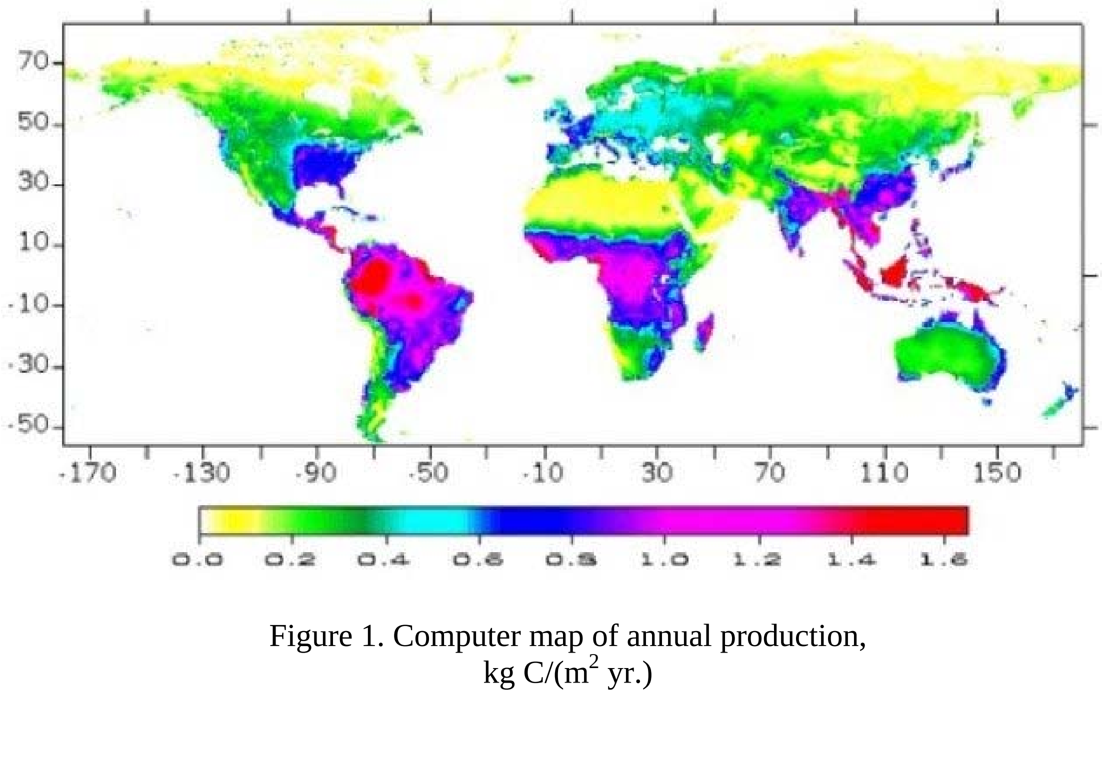

Figure 1. Computer map of annual production,
kg C/(m^2 yr.)

A computer calculated map humus storage adequately reproduces its distribution all over the Earth. The maximum values of humus are reproduced in grassland ecosystems, containing chernozems.

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Biographical Sketch

Alexander M. Tarko, Dr. Sci. (1992), Ph.D. (1978) is a Senior Research Fellow of Computing Center of the Russian Academy of Sciences, Moscow, Russia. He is a Professor of Mathematical Cybernetics at Moscow Institute of Physics and Technology and since 1993 gives lectures on System Analysis, Mathematical Ecology, and Problems of Environment. In 1995 he was elected as Academician of International Informatization Academy and in 1996 as Academician of Russian Academy of Natural

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Since 1975 he has been dealing with problems of human impacts on the biosphere. His particular field of research was modeling global and regional biogeochemical cycles of carbon dioxide and nitrogen in biosphere. He developed a mathematical approach to investigate the biosphere stability, created a set of mathematical models of the biosphere and received forecasts of biosphere dynamics.

Now his research focuses on developing high resolution spatially distributed models of global biogeochemical cycles, simulating the spatial regional atmospheric pollution impact on forest ecosystems, investigating the principles of biosphere and society self-regulation, and the sustainable biosphere development principle. He also works in understanding the evolution of human civilization under the degradation of biosphere resources, and its renewal as the result of scientific and technical progress.

Principal investigator of several governmental grants, expert in the Expert Committee of the Russian Ministry of Nature Resources, he divides his time between fundamental science, environmental consulting, and teaching. His research is reported in more than 150 publications.