*The Global Role of the Biosphere in the Stabilization of Atmospheric CO_2 and Temperature**

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ABSTRACT

The global role of an atmosphere-plants-soil (APS) system in the formation of the CO_2 and temperature regime of the atmosphere under anthropogenic actions is investigated. For this purpose a mathematical model of the global carbon cycle in the APS system has been developed. The APS model consists of two sub-models: grassland and forest systems. The model deals with the dependence of biological processes on the atmospheric CO_2 concentration and atmospheric temperature, and also with the dependence of atmospheric temperature on the atmospheric CO_2 concentration (greenhouse effect).

The ability of the APS system to compensate for different types of anthropogenic actions on the biosphere is considered. Simulated experiments show that the APS system could absorb approximately half of all the CO_2, released by industries between 1860–1970. They also show that a unit area of the forest system is able to absorb more CO_2 releases, and do this more rapidly than the grassland system. However, no reliable information could be obtained as to the ability of the APS system to compensate for heating influences on the atmosphere.

Estimation of the absorption potential of the APS system and the ocean shows that atmospheric CO_2 will, by the year 2000, increase to 387–398 ppm by volume and the temperature will increase by 0.39°–0.45°C in comparison with 1970.

INTRODUCTION

Atmospheric CO_2 is one of the components of the global carbon cycle. The main form of carbon in the atmosphere is CO_2 which, owing to the "greenhouse effect", exerts an influence on the Earth's climate. On one hand, atmospheric carbon is used by photosynthesizing plants for biomass growth; on the other hand, it is released during the decay of dead organic matter.

*This report is a short survey of the work by the authors on modelling of the global carbon cycle in the biosphere. Complete information is reported in: Yu.M. Svirezhev, A.M. Tarko, Problem of ecological equilibrium of biosphere and biogeochemical cycles. In: Methods of system analysis in problem of rational usage of resources. Computation Center, USSR Academy of Sciences. Moscow, 1977 (in Russian).

CO_2 concentration and climatic factors determine the rates of biological processes such as the assimilation of CO_2 by terrestrial plants and the decay of dead organic matter in soils. The dynamics of CO_2 in the atmosphere depend inter alia on the balance between these two processes. The annual input of CO_2 into the atmosphere, and its removal, are estimated to be about 10% of all atmospheric CO_2 (Bazilevich *et al.,* 1971). Besides, the CO_2 dynamics obviously depend on the exchange between the ocean and the atmosphere. It is also necessary to take into account the releases of CO_2 as a result of forest fires and volcanic activity.

The carbon cycle is also influenced by anthropogenic factors. For example, the annual release of fossil fuel CO_2 makes up about 1% of the total atmospheric CO_2 and about 10% of the CO_2 being consumed by plants. As another example, the forests are being cut down, and vegetation-covered areas are being reduced. The scale of anthropogenic influences is continuously growing.

The aim of this work is to estimate the global role of the "atmosphere-plants-soil" system (APS) in the formation of the gaseous and temperature regime of the atmosphere under anthropogenic influences in the biosphere. With this in view, we have built a mathematical model of the global carbon cycle and we have carried out simulation experiments.

A MODEL FOR THE CARBON CYCLE (THE MODELLING PRINCIPLES)

The main objective of our work is to describe the carbon cycle in the land biosphere. We treat exchange processes between the ocean and the atmosphere using Machta's model (1971), or by assuming a constant flux.

The duration of processes to be considered in the model is of the order of tens and hundreds of years. This time scale is far shorter than that of geological processes, which can, therefore be ignored. So we assume that without disturbing factors (human activity and so on) the total quantity of carbon in the APS system is constant. In addition, we can suppose that the APS system was in a steady state before the beginning of the industrial era. Suppose that all or almost all the biogeocenoses have similar functional characteristics. Then we can choose a high degree of aggregation and consider the whole APS system as a community of two systems: grassland and forest (fig. 1).

The model is described by a system of ordinary differential equations which is presented in terms of Forrester's "system dynamics" (1961). The quantities of carbon in the levels shown in fig. 1 are denoted by N_i, where i is the number of the corresponding level (i = 1, 2, . . ., 8). The rate of carbon flow from level i to level j is denoted by F_{ij}. The initial values of N_i and F_{ij} are denoted by N_i^o and F_{ij}^o and their stationary values by N_i^* and F_{ij}^*. The time unit of the model is one year. In our model the so-called "temperature" (T) is the difference between the mean annual temperature of the Earth's surface and the value of this temperature at the present time (15°C). The dependence of temperature on CO_2 concentration in the atmosphere ("green-house

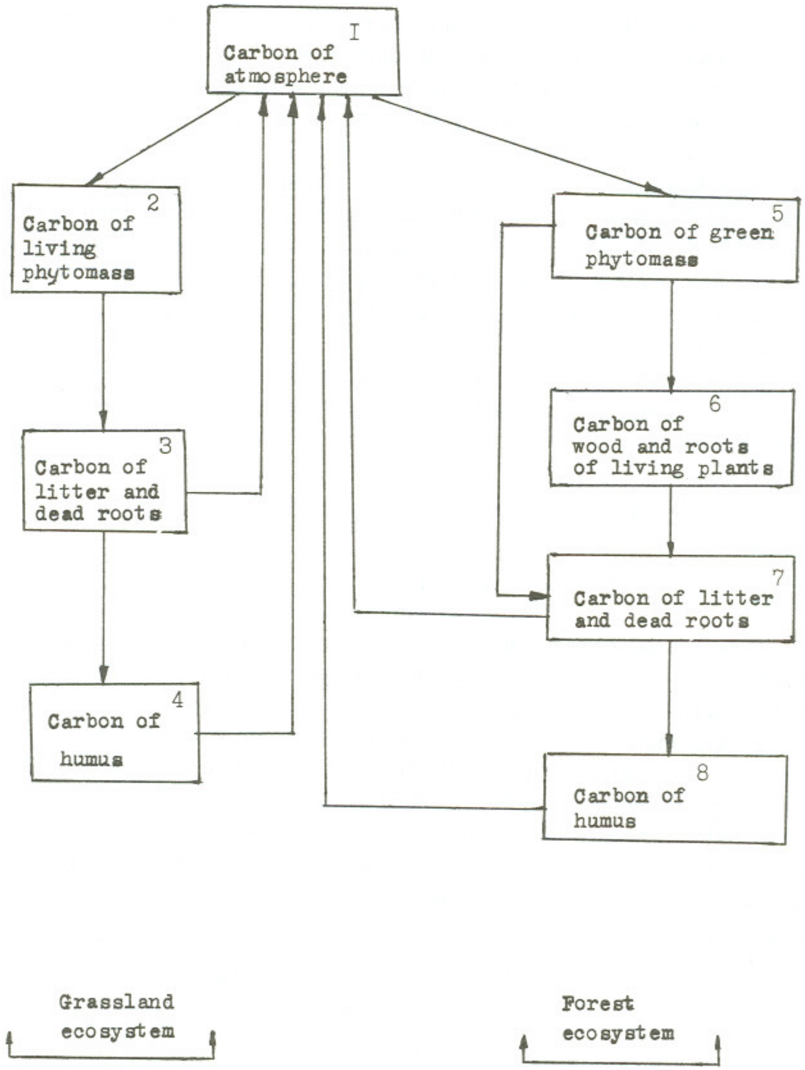

Figure 1: Diagram of flows of carbon in the model of atmosphere – plants – soil system.

effect") has been taken from results of Rakipova and Vishnyakova (1973) in which the dependence on humidity was neglected. The following equations were used:

$$T = \begin{cases} 2.5\,(1 - \exp(-0.81\,(Z_1 - 1)) + E & \text{if } Z_1 > 1 \\ -5.25Z_1 + 12.55Z_1 - 7.3 + E & \text{if } Z_1 < 1 \end{cases}$$

where $Z_1 = N_1/N_1^0$ and E denotes an external disturbance of the temperature.

We suppose that the external disturbances are rather small and that the system does not go far from the steady state, i.e. all the system trajectories lie in the neighbourhood of the corresponding stationary point. Owing to this we can assume that the productivity of the system does not depend on the quantity of the nutrient elements in the soil and depends only on climatic factors.

For the validation of the model we have used data from Bazilevich *et al.* (1971), Bazilevich (1974), Bazilevich and Titlyanova (1975). In cases where these data have been used to derive values of carbon quantities in levels, rates and coefficients, then analogous data of other authors (Duvigneaud and Tanghe, 1967; Lieth, 1973) have been used to check the model's adequacy. The data of humus stocks in soils have been taken from Kovda (1975).

The flow diagram is shown in fig. 1. The consumption rate of atmospheric carbon (in CO_2 form) by plants (photosynthesis minus respiration) can be represented by the following equation:

$$\underset{i=2,5}{F_{1i}} = \begin{cases} f_i \left(1 + \dfrac{\alpha_i}{100} T\right) \left[1 + \dfrac{\delta_i}{10} \left(\dfrac{N_1}{N^\circ_1} - 1\right)\right] S_i = F_i & \text{at } F_i \leqq K_i F^\circ_{1i}, \\ K_i F^\circ_{1i} & \text{at } K_i V^\circ_{1i} < F_i, \end{cases}$$

where the indices i = 2 and i = 5 deal with the grassland and forest systems respectively; f_2 and f_5 are their productivities; S_2 and S_5 are relative values of the areas which are occupied by grassland and forest systems. The coefficients α_i and δ_i give the percentage increase in productivity for a temperature increase of 1°C or an atmospheric CO_2 concentration increase of 10% in comparison with present-day values of these variables. The coefficients K_i determine the limit of the productivity.

The productivity of different biogeocenoses may not only increase, but also decrease as a result of a temperature increase (under constant humidity and cloudiness). We consider values of α_2 α_5 from −4 to 15 to be realistic.

The dying rate of woods and roots in the forest system is given by:

$$F_{67} = \begin{cases} mN_6 & \text{at } N_6 \leqq K_6 N^\circ_6 \\ F_{56} & \text{at } N_6 > K_6 N^\circ_6 \end{cases} \tag{2}$$

where the coefficient m denotes a specific rate of dying of woods and roots. The coefficient k_6 denotes the possible limit of relative magnitude of wood and root biomass (in comparison with present-day values) when the death rate of trees is increased, and the growth of N_6 stops.

The corresponding rates of humus decay can be written as

$$\underset{i=4,8}{F_{i1}} = \begin{cases} f_i \exp\left(\dfrac{\ln Q}{10} T\right) N_i & \text{at } \exp\left(\dfrac{\ln Q}{10} T\right) \leqq K_i \\ f_i K_i N_i & \text{at } \exp\left(\dfrac{\ln Q}{10} T\right) > K_i \end{cases} \tag{3}$$

where f_4 and f_8 are the specific rates of humus decay in present-day conditions. Here, Q is a coefficient which denotes how the decay rate changes if the temperature changes by 10°C. The observed values of Q vary from 2.6 to 2.9 (Reichle, 1971). K_i gives the limit of temperature beyond which the decay rate does not increase.

If there are no external flows of carbon in the atmosphere from other sources, then the system posseses the integral property

$$\sum_{i=1}^{8} N_i = M = \text{const.} \qquad (4)$$

Though concrete expressions for some flows are known, we cannot formulate the corresponding expressions for other processes of carbon transport because of lack of knowledge. Nevertheless there seems to exist a way out of this seemingly difficult situation. This is connected with the existence of a time-scale hierarchy in our system. It should be noted that the characteristic time of dying for green phytomass and litter decay is on the order of a year, and is far less than the characteristic time considered in the model. This circumstance enables us to use the Tikhonov theorem, and to reduce the dimensions of the model. Without loss in accuracy, we can assume that $\dot{N}_2 = \dot{N}_3 = \dot{N}_5 = \dot{N}_7 = 0$.

In order to describe the model completely, we have formulated the additional hypothesis: if the total carbon flow which goes out from some functional block (in our case the blocks or levels of numbers 3, 5, 7) is divided into two subflows, then the ratio of their rates is practically a constant. For example,

$$\lambda_7 = \frac{F_{56}}{F_{57}} = \text{const} \quad \text{(see fig. 1).}$$

This hypothesis is proved by the experimental data, especially for taiga, steppes and prairies).

ANALYSIS OF THE MODEL AND SIMULATION EXPERIMENTS

For the analysis of the model we have used a combination of two approaches:

1. An analytical investigation, where we suppose that all the area of the APS system is occupied by either grassland or forest. We shall call such systems either grassland or forest, respectively.

2. Simulation modelling of the system's responses to different external and internal disturbances. We shall suppose, first, that the terrestrial area is occupied only by a grassland or a forest system, and, finally, by the system with the actual distribution of ecosystems on the Earth's surface. The initial state of the system is calculated from the assumption of initial steady state, with data as in Table 1.

In these computing experiments, we simulated the results of human activity in the biosphere. Therefore, qualitatively and quantitatively, the role of the APS system has been studied as the cause of changes in the atmosphere (the evolution of its gaseous and temperature regimes).

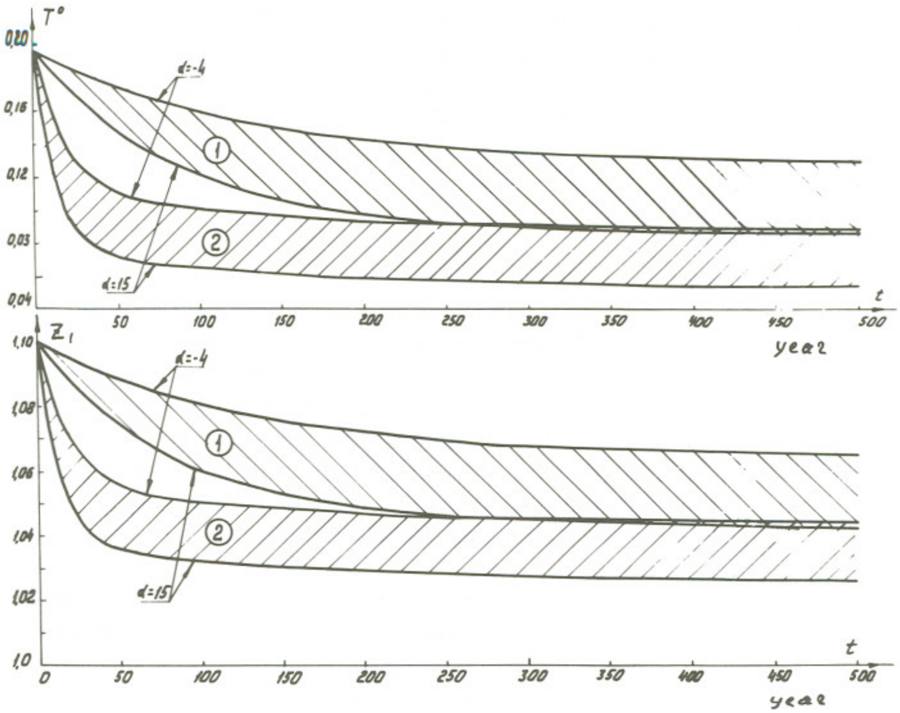

Figure 2: Changes of the temperature and CO_2 concentration in atmosphere in response to an instant increase of CO_2 in the atmosphere by 10%. 1 – range of trajectories for the grassland system; 2 – range of trajectories for the forest system. Values of $\alpha_2 = \alpha_5 = \alpha$ vary from −4 to 15.

It has been shown that equilibrium states of the system are stable for a broad interval of carbon quantities which may be contained in the APS system and for real values of paramters. (The considered interval is from 50% to 200% where the level of 100% is the CO_2 concentration in the atmosphere at present). Furthermore, there are no oscillations in the system.

The fossil fuel releases into the atmosphere lead to an increase of atmospheric CO_2 concentration, and hence to an increase of temperature. In turn, these increases give rise to such an inbalance in the carbon flows that part of the CO_2 releases is absorbed by the APS system thereby causing the temperature to decrease slightly.

The sufficient condition for the APS system to be able to absorb part of the CO_2 releases into the atmosphere can be formulated as follows.

The projections of the equilibrium status curve $N_i(M)$ ($i = 1, 4, 6, 8$) on each of the coordinate planes (N_1, N_i) ($i = 4, 6, 8$) must be monotonically increasing functions of N_1.

It has been shown that this condition is fulfilled for all actual values of the parameters. It means that the APS system responds to this kind of disturbance (fossil fuel

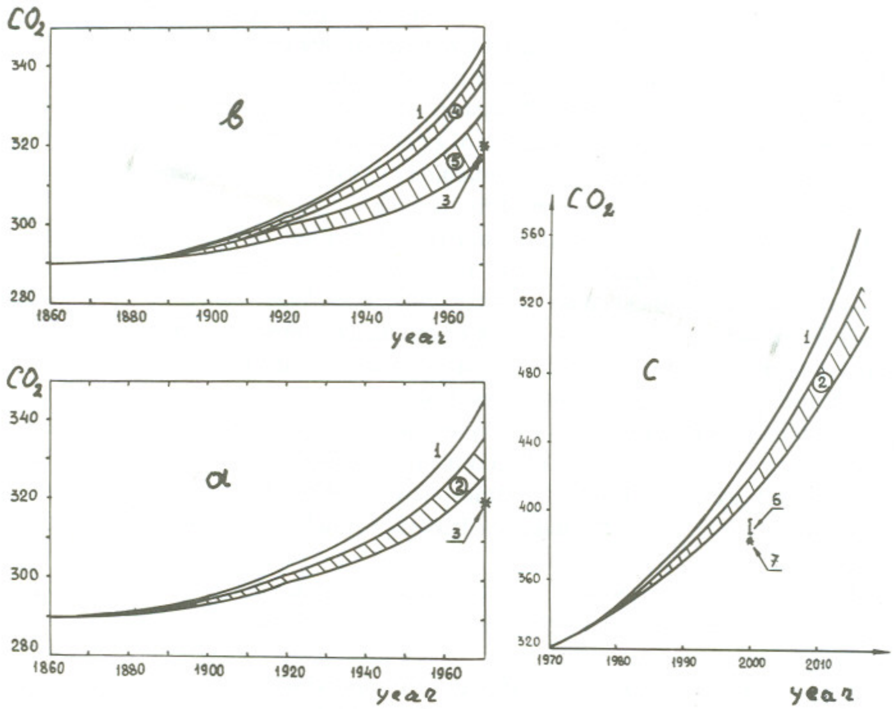

Figure 3: Estimation of the role of the APS system in the absorption of industrial releases of CO_2 during 1860–1970 (a, b) and after 1970 (c). a – change of atmospheric CO_2 in the APS system, b – the same but if the whole APS system is either a grassland system or a forest system. Curve 1 – change of CO_2 without absorption; 2 – change of CO_2 in the presence of the APS system with $S_2 = 0.61$ and $S_5 = 0.39$; 3 – real concentration of CO_2 in 1970; 4 – The APS system is assumed to be the grassland system; 5 – the APS system is assumed to be the forest system; 6 – forecast of atmospheric CO_2 concentration in the year 2000 in the presence of the APS system and the ocean; 7 – Machta's forecast: 2, 4, 5 – the tubes of trajectories at a realistic range of parameters. The CO_2 concentration is measured in p.p.m. by volume.

releases) in accordance with Le Chatelier's principle, i.e. it seeks to compensate for these influences.

The changes of temperature and CO_2 concentration in the atmosphere ($Z_1 = N_1/N_1^\circ$) in the grassland system and in the forest system, in response to an instant increase of CO_2 in the atmosphere by 10% (in comparison with present-day value) are shown in fig. 2. The forest system seems to be able to absorb 56–74% of all the releases and the grassland system is able to absorb 35–57%. The forest system is able to absorb the excess of atmospheric CO_2 much faster than the grassland system. For example, the time of absorption of half of all the eventually absorbed CO_2 is 10–16 years for the forest system and is 60–90 years for the grassland system.

Estimation of the role of the APS system in absorbing industrial releases of CO_2 between 1860–1970 is represented in fig. 3a. The values of average decade releases of CO_2 are taken from Robinson and Robbins (1972). The real increase of CO_2 concentration between 1860–1970 is 54% of all the releases. Simulations show that the APS system has absorbed 18–34% of the CO_2 releases during the same period. The rest (12–28%) has obviously been absorbed by the ocean.

This evidence shows that the APS system could absorb approximately half of all the absorbed CO_2. So the APS system is of great importance in the absorption of the CO_2 excess and, consequently, in maintaining a constant level of atmospheric CO_2 concentration, and in stabilization of the climate.

It is necessary to point out the important role of the forests, since, according to the model (see fig. 2 and 3 b), a unit area of the forest system is able to absorb more CO_2 and to do this more quickly than the grassland system. This result does not depend on differences between the parameters of productivity processes in grassland and forest systems respectively, but it is explained by the dynamics of carbon accumulation in the wood and roots of the forest system.

An estimation of the role of the APS system in absorbing industrial releases of CO_2 in the future is shown in fig. 3c. In accordance with Robinson and Robbins (1972) industrial releases of CO_2 into the atmosphere in 1970 were 17 gigatons. Annual growth rates are 4% until 1980 and 3,5% thereafter. (Study of Critical Environmental Problem, 1970).

Without absorption, the CO_2 concentration in the atmosphere would be 36% higher by the year 2000 than in 1970. The APS system will be able to absorb 11–21% of the releases during this period. If we assume that the ocean will absorb 20% of all released CO_2 (as was the case from 1860 to 1970 approximately), then 31–41% of all the CO_2 releases during this period will consequently be absorbed. Hence, the concentration of atmospheric CO_2 will increase by 21–24% (387–398 ppm by volume) in comparison with 1970. This forecast is in good agreement with the forecast of 380 ppm (Study of Critical Environmental Problem (SCEP) 1970) and 375 ppm by Machta (1971), although these forecasts were obtained in different ways. According to our forecast, the increase of temperature will be 0.39°–0.45°C.

For the APS system to be able to compensate for purely heating influences on the atmosphere, it is necessary that

$$\frac{\dot{N}_1}{T} < 0$$

If this condition is fulfilled, heating of the atmosphere will lead to an increase in the intensities of biological processes. As a result, the concentrations of atmospheric CO_2 will decrease and the temperature rise will be somewhat less. When this condition is not fulfilled, heating of the atmosphere will lead to an increase of CO_2 concentrations and to some further heating of the atmosphere.

It is necessary to note that we have no reliable information on the ability of the APS system to compensate for these kinds of influences.

We consider the following situation. Let the temperature of the atmosphere increase every year by 0.5°C, in addition to the greenhouse effect. In this way we simulate some thermal action on the atmosphere. The CO_2 concentration and atmospheric temperature will change as shown in figures 4 and 5. It can be seen that

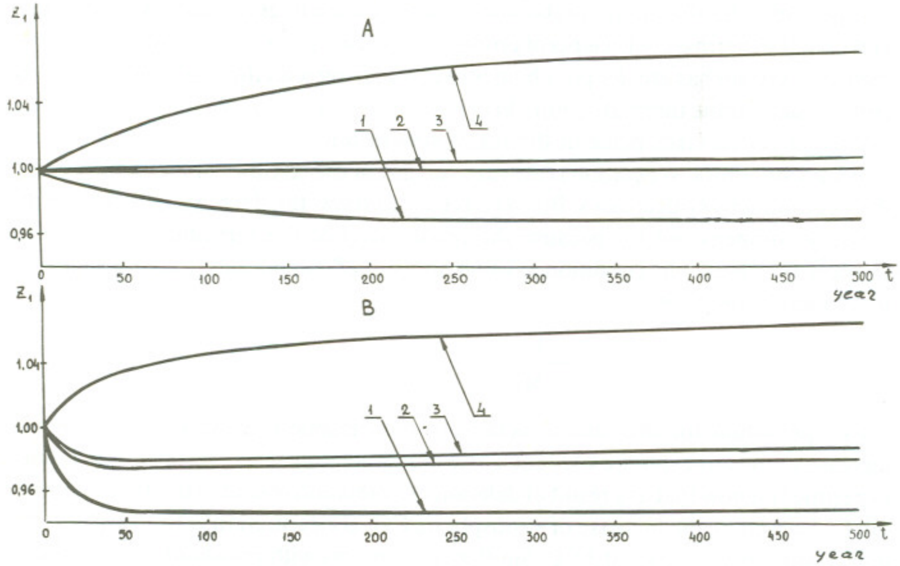

Figure 4: Change of atmospheric CO_2 concentration with the heating action on the atmosphere of the APS system. A – all the ABS system is a grassland system. B – all the APS system is a forest system.

$1: a_2 = a_5 = 15$; $2: a_2 = a_5 = 7.2$; $3: a_2 = a_5 = 6$; $4: a_2 = a_5 = -4$.

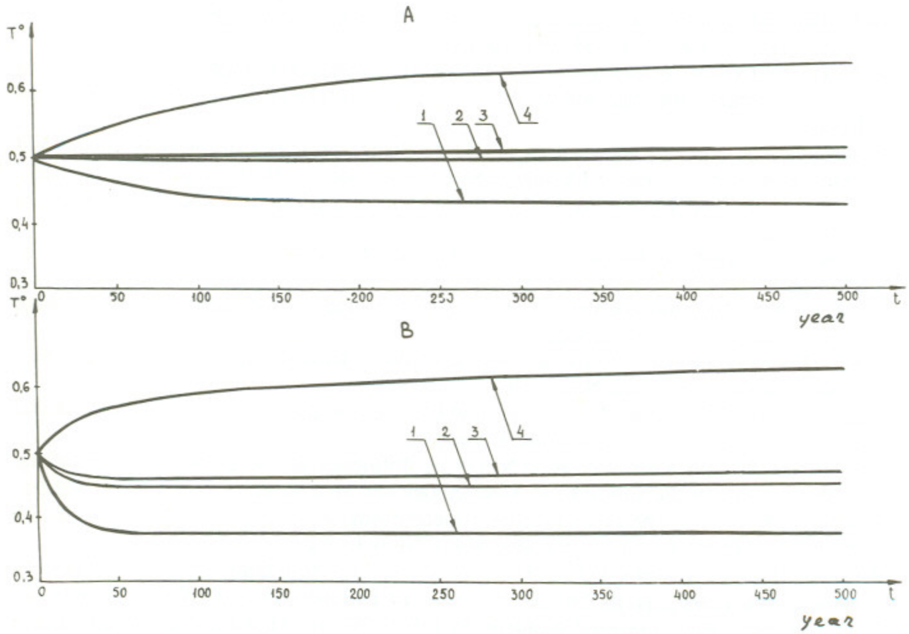

Figure 5: Change of temperature with the heating action. Notation is as in fig. 4.

compensation for the thermal action on the atmosphere does not take place at all the values of the thermal coefficients of productivity α_2 and α_5. It is necessary to note that the forest system has greater possibilities in comparison with the grassland system, to compensate for the thermal action: At Q = 2 and $\alpha_2 = \alpha_5 = 7.2$, compensation for the simulated action takes place in the forest system only.

As a result of the vegetation removal over part of the territory of the APS system, the net productivity decreases. But, as it is easy to show, the decrease of productivity is partly compensated for because the productivity of the remaining parts of the territory increases. The condition in which this sort of compensation takes place may be written in the form:

$$\frac{F_{12}}{N_1} > 0; \frac{F_{15}}{N_1} > 0.$$

Compensation for this sort of action on the biosphere is accompanied by an increase of the atmospheric CO_2 and a rise of temperature. For example, simulation experiments show that as a result of deletion of vegetation over 20% of the territory of the forest system, the increase of atmospheric CO_2 concentration is 13−19% and the temperature rise is 0.24°−0.39°C. Similar experiments with grassland systems show an increase of atmospheric CO_2 by 20−27% and a rise in temperature of 0.37°−0.5°C.

The simulation experiments showed that the use of some of the territory of the APS system for agriculture weakens the compensatory potential of the APS system.

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