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Recently-performed research on developing simulation methods has /37*
made it possible to construct a general model of the biosphere involving socio-economic, physico-chemical, and ecological processes. In following the basic concepts in models of the D. Forrester [1971] type, we shall consider the cause-and-effect links existing in the biosphere between such elements as the energy of solar radiation (E), the concentration of CO_2 (C) and O_2 (O), atmospheric turbidity (B), temperature (T), population (g, G), humus (S_g, S_G), and the nekton (r) and phytoplankton (ϕ) in the world's oceans (fig. 1). We shall divide dry-land vegetation into three types, differing in productivity and participating with varying degrees of intensity in other ecological processes: forests (P_L, Q_L), agricultural vegetation (P_X, Q_X), and other vegetation ($P_{\overline{L}}$, $Q_{\overline{L}}$).

In order to calculate socio-economic heterogeneities existing in the biosphere, dry-land area ($S = 0.73805 \times 10^8$ km^2) is divided into two regions, in each of which the processes under study may proceed at differing rates.

It is given that a solar radiation energy of $E_o = 1.94$ cal/cm^2 min. enters the biosphere and is used by biospheric photosynthetic elements. Here the value of E (t) reaching the Earth's surface is determined by /39
the atmosphere's turbidity and may be calculated using the formula $E(t) = E_o(t) \cdot \exp(-\alpha B - \beta)$, where the coefficient of atmospheric absorption of solar energy due to dust and clouds $\alpha = 11.643 \times 10^{-4}$, and the transparency index of the pure atmosphere $\beta = 6.487$. The dustiness of the atmosphere is determined by the number of atmospheric dust particles resulting from dust storms (5.4×10^7 tons/year), volcanic eruptions, solid and liquid fuel combustion (4.3×10^9 tons/year), and expulsion from various kinds of metallurgical and chemical works, cement plants, and other sources (15×10^9 tons/year).

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*Numbers in the margin indicate pagination in the foreign text.

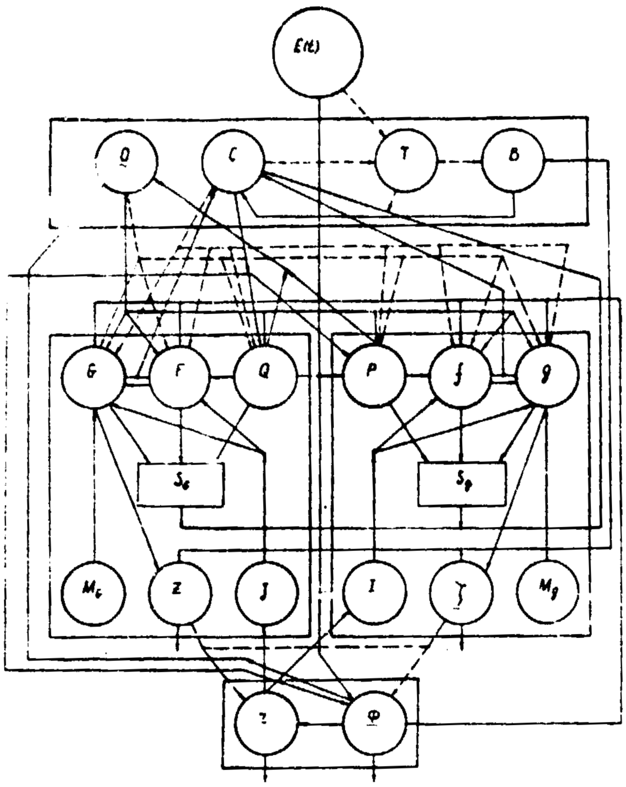

Fig. 1. Diagram of the cause-and-effect ties in the global biogeocenotic biosphere simulation. Designations are explained in the text. /38

It is considered that in ocean and dry-land areas the coefficients of solar energy use are $K_\phi = 0.07$, $K_P = K_Q = 0.5$. The productivity of the ocean and land ecosystems is determined by the intensity of photosynthesis, which depends upon the discrepancy between optimal and actual illumination, the amount of fertilizers applied, and pollution in the corresponding environments. The quantity of applicable fertilizers is determined by the proportion of expendable mineral resources (U_g, U_G). Phytomass production increases in proportion to the increase in atmospheric CO_2 concentration until $C^* = 0.2\%$ and decreases in proportion to the increase in O_2 content to approximately $O^* = 21\%$, so that /39

$$K_i = K_i'(C) \times K_i''(O) \quad (i = P, Q)$$

As in the work of M. E. Vinogradov et al. (1973), we shall write differential equations describing the change in phytomass (in tons/km^2):

$$\frac{d\Phi}{dt} = R_\Phi - M_\Phi - t_\Phi \Phi - R_r - \left(\frac{K_{g\Phi} R_g}{V_g} + \frac{K_{G\Phi} R_G}{V_G}\right)\Phi,$$

$$\frac{dP}{dt} = R_P - M_P - t_P P - \left(\frac{K_{fP} R_f}{V_f} + \frac{K_{gP} R_g}{V_g}\right)P,$$

$$\frac{dQ}{dt} = R_Q - M_Q - t_Q Q - \left(\frac{K_{FQ} R_F}{V_F} + \frac{K_{GQ} R_G}{V_G}\right)Q,$$

where R_ϕ, R_P, and R_Q are the rates of increase in ϕ, R, and Q, subject /40
to illumination, the concentrations of CO_2 and O_2, and environmental pollution. R_P and R_Q also depend upon the distribution of sub-forest

areas (S_L) and agricultural vegetation (S_X). The formula for R_P, for example, is:

$$R_p = \kappa_p P A_p E E_p^{*-1} \exp[m_2(1 - E E_p^{*-1})][1 - \exp(-\gamma_2 P)],$$

where

$$A_p = A_p^* \left[\frac{S_L^{(1)} B_L^{(1)} + S_X^{(1)} B_X^{(1)}}{S_1} + \left(1 - \frac{S_L^{(1)} + S_X^{(1)}}{S_1}\right) B_{\bar{L}}^{(1)}\right].$$

Here E_P^* is the optimal illumination for photosynthesis P (kcal/m^2/day); $B_L^{(1)}$, $B_X^{(1)}$, and $B_{\bar{L}}^{(1)}$ are P/B coefficients for L, X, and $\bar{L}$, respectively; A_P^* is the coefficient of proportionality; M_ϕ, M_P, and M_Q are the rates of ϕ, P, and Q desiccation; t_ϕ, t_P, and t_Q are values for energy exchange expenditure; K_{ij} is the coefficient reflecting the value for the quota and proportion of the producer "j" in the nutritional allowance R_i of consumer "i" (i,j = g, ϕ, P, Q, f, G, F).

We shall assume that nekton is harvested by the regions at intensities of $\lambda_g(t)$ and $\lambda_G(t)$, maximum P/B is the coefficient r equal to K_r, and the limitation in growth of r because of pollutions ζ and Z in regions 1 and II are described by the function $\psi = \exp[-dr(\rho\zeta + \theta Z)]$, where ρ and θ are proportions of all pollutions falling from regions 1 and II into the ocean. Thus the change in biomass r (tons/km^2) may, as in the work of M. E. Vinogradov et al. (1973), be described by the equation:

$$\frac{dr}{dt} = R_r - (\mu_r + \lambda_g + \lambda_G) r - t_r r^{\omega_r},$$

where

$$R_r = \kappa_r r [1 - \exp(-\kappa_{r\Phi} \Phi)] \Psi,$$

μ_r is the instantaneous mortality rate, and t_r is the value for energy exchange expenditure.

We shall describe the population growth in both regions by calculating the relationship of birth and mortality rates to the nutrition equation $F_{R\alpha} = V_\alpha/\alpha$, the material standard of living /41

$$V_{Si} = V_i (1 - S_i - U_{Ri} - U_{Zi}) E_{Ri} [i (1 - S_{Oi}) E^0_{Ri}]^{-1},$$

environmental pollution, atmospheric CO_2 and O_2 content, and population density. Here V_i is the principal (basic resources) of the i region; S_i, U_{Ri}, and U_{Zi} are the proportions of principal investments for the i region in the development of agriculture, renewal of mineral resources, and environmental conservation, respectively.

The equation for g is:

$$\frac{dg}{dt} = R_g - \mu_g g - t_g g^{\omega_g},$$

where

$$R_g = \kappa_g g\left(1-e^{-V_g}\right)\left(1-e^{-\kappa_{go}O}\right)e^{-\kappa_{gc}C}\left(a_b^{*} + a_b' e^{-r_b M_{sg}}\right)\times$$
$$\times\left(c_b' + c_b^{*}\exp\left[-c_b'' \frac{g}{g_0}\right]e^{-l_b'' z_R}\right),$$
$$\mu_g = \mu_g'\left(b_d' + b_d'' e^{-b_d M_{sg}}\right)\left(\theta_d' + \theta_d'' g^{\omega_d}\right)\left(\rho_d' + \frac{\rho_d''}{F_R}\right)\times$$
$$\times\left(n_d' + n_d'' z_R^{n^*}\right)e^{\kappa_{\mu}C}\left(f_0' + f_0'' O^{-1}\right), \quad z_R = \zeta/\zeta_0,$$
$$\varepsilon_{Rg} = 1 - \exp\left[-\kappa_\varepsilon M_g(t)/M_g(t_0)\right], \quad V_{Rg} = V_1/g,$$
$$V_g = \kappa_{g\Phi}\Phi + \kappa_{gf} f + \kappa_{gr} I\,(1-u-v) + \left[\left(\kappa_{gp}' S_L^{(1)} + \right.\right.$$
$$\left.\left. + \kappa_{gp}'' S_X^{(1)}\right)S_1^{-1} + \left(1 - \frac{S_L^{(1)} + S_X^{(1)}}{S_1}\right)\right]P.$$

The equation for G is similar in form.

Change in animal food in both regions is determined by the rate of animal growth, which depends upon the gaseous makeup of the atmosphere, the availability of a vegetable diet for animals, mortality rate, rate of energy exchange with the environment, and consumption by the populace. The equation for f, for example, has the following form:

$$\frac{df}{dt} = R_f - \mu_f f - t_f f^{\omega_f} - \kappa_{gf} f R_g V_g^{-1},$$

where /42

$$R_f = \kappa_f f\left(1-e^{-V_f}\right)\left(1-e^{-\kappa_{fo}O}\right)e^{-\kappa_{fc}C},$$

$V_f = K_{fP}P + K_{fr}IV$, and V is the amount of harvestable nekton needed by the animals.

In order to calculate the physiological effect of O_2 and CO_2 concentrations in living organisms, we shall cite the following relationship of the expenditure and energy exchange of element "a": $t_a = t_a' \cdot t_a''$, and

$$t_a' = \begin{cases} t_{a1}' C + t_{a0}', & C > C_a; \\ t_{a0}', & C \in [0, C_a]; \end{cases} \qquad t_a'' = \begin{cases} t_{a0}''', & O > O_a; \\ t_{a0}'' - \frac{O}{O_a}\left(t_{a0}'' - t_{a0}'''\right), & O \in [0, O_a] \end{cases}$$

These relationships reflect the increased respiratory expenditure of animals and humans, with a CO_2 concentration elevated beyond the threshhold of C_a and an O_2 concentration below O_a.

We shall descibe the effect of human agricultural activity on the environment by calculating the amount of energy required for population respiration, mineral resource utilization, and the generation of pollution. We shall calculate possible ways to manage these elements which will make it possible to prevent environmental degradation by organizing the intelligent use and conservation of resources, and by imposing closed production cycles which fully utilize wastes and pollution. Without detailing methods for achieving control, we shall propose that the following time functions are characteristic for the scientific and technological progress of both regions: K_ζ (K_Z) is the pollution generation per individual person (a characteristic of the standard of living and the technology of production in a society); T^*_ζ (T^*_Z) is the pollution resorption rate index; M_g (M_G) is the intensity of non-renewable resource expenditure; $T^{(i)}_{HT}$ is the time interval necessary for transfer to new resources in the i region; $t^{(i)}_X$ and $t^{(i)}_B$ are the times needed by the i region for maximum incorporation of all lands suitable for cultivation and achievement of the maximum possible productivity for agricultural cultivation. /43

We may write the following equation to describe the process of pollution generation and utilization (1st region):

$$\frac{d\zeta}{dt} = \kappa_\zeta(t) g Z_{Vg} - \frac{\zeta}{T_\zeta(t)} - U_{\zeta g} V_1 C^{-1}_{Zg} ,$$

where

$$Z_{Vg} = Z^{max}_{Vg}[1 - \exp(-\hat{C}_{\zeta g} V_{Rg})], \qquad C_{\zeta g} = C''_{\zeta g} + C'_{\zeta g} \exp[-n_{\zeta G}(t - t_0)],$$

$$T_\zeta(t) = T^*_\zeta(t)[a'_{Zg} + a''_{Zg} Z^{\rho_{Zg}}_{Rg}].$$

We shall describe the change in biospheric gaseous makeup by calculating the following natural and anthropogenic processes. Assume that O_2 and CO_2 exchange between the atmosphere and ocean is described by L. Makht's (1971) model, the source of O_2 output on dry land is the phytomass, O_2 consumption occurs during respiration of element "a" at a rate of $\gamma_a = \nu_a t_a a^{\omega_a}$ and takes place in the resource combustion process at rates of b_{go} and b_{GO} per person in regions 1 and II, respectively. Carbon is assimilated by the plants of region 1 (II), in the form of CO_2 from the atmosphere, at rates of $\Theta'_{PC} R_P$ ($\Theta'_{QC} R_Q$) by forests, $\Theta'_{XP} R_P$ ($\Theta'_{XQ} R_Q$) by agricultural vegetation, and $\Theta''_{PC} R_P$ ($\Theta''_{QC} R_Q$) by other types of plants; it is liberated in the process of element "a" respiration at a rate of $\beta_a = \psi_a t_a a^{\omega_a}$, given off during resource combustion at a rate of b_{gc} (b_{GC}), and by the decomposition of dead vegetation at a rate of μ_S.

We shall describe atmospheric turbidity with the following equation:

$$\frac{dB}{dt} = N_1 \Xi + N_2 Z + N_3 b_{gc} g + N_4 b_{GC} G - \frac{B}{T_G} + \rho_B \frac{dT}{dt}$$

where N_1 and N_3 (N_2 and N_4) are the amounts of pollution and smoke generated by region 1 (II) into the atmosphere, ρ_B is the rate of cloud cover alteration due to temperature fluctuations, T_G is the rate of natural clarification of the atmosphere due to dust settling. We shall /44 present the following relationship between temperature, illumination, and alterations in biosphere gaseous makeup through the use of models such as that described by M. I. Budyko (1971).

The remaining model equations, reflecting the dynamics of mineral resource alteration M_g (M_G), the principal V_1 (V_2) and capital investment S_1 (S_2) in agriculture investment for region 1, have the following form (Gelovani et al., 1976):

$$\frac{dM_g}{dt} = -m_g(t) R_{Mg} g + V_1 U_{Rg} G_{Rg}^{-1},$$

$$\frac{dV_1}{dt} = C_{Vg} V_{Mg} g - V_1 T_{Vg}^{-1},$$

$$\frac{dS_1}{dt} = (U_{Sg} S_{Fg} S_{ag} - S_g) T_{Sg}^{-1},$$

where $R_{Mg} = a_{Rg} \ln(1 + M_{Sg})$, $C_{Rg} = C_{Rg}^{*} + C_{Rg}^{0} e^{-u_{cg}(t - t_0)}$,

$$V_{Mg} = \kappa'_{Mg} \ln(1 + \kappa''_{Mg} M_{Sg}), \quad S_{Fg} = \exp(-b_{Sg} F_{Rg}),$$

$$S_{ag} = b'_{Sg} + b_{Sg} (b'_{ag} + b''_{ag} M_{Sg}^{\alpha_{ag}})^{\alpha_{Sg}} [a_{ag} F_{Rg}^{\beta_{ag}}]^{-\alpha_{Sg}}$$

The model described above has been expressed in FORTRAN in the form of a program for the UVK M-4030. Calculation of all its components for 100 years requires 1 hour of machine time, which makes it possible to carry out assorted experiments on the model.

The prognosis for biosphere condition without any management and maintenance of rates of natural resource utilization, pollution generation, forest reduction, etc., is shown in fig. 2. Here, beginning in the year 2050, population density will fluctuate while maintaining a general

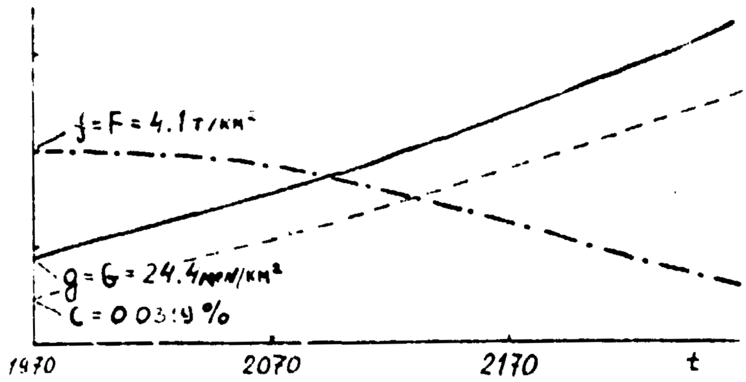

Fig. 2. Prognosis for biospheric component dynamics if contemporary rates of natural resource utilization are maintained. Explanation of the designations may be found in the text. Values for variables are in relative units. Their values in 1970 are shown.

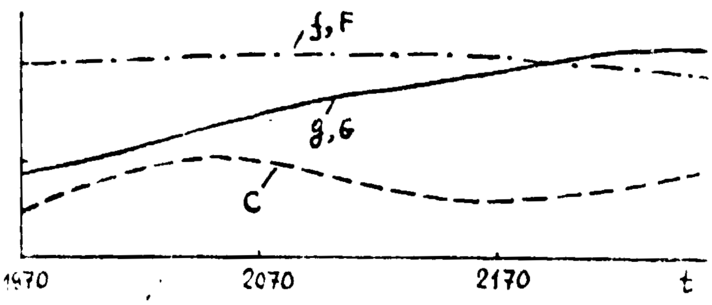

Fig. 3. Prognosis for biospheric component dynamics if rates of influence on the biosphere and distribution of capital investment are decreased. Explanation in the text. Designations are the same as in fig. 2.

tendency to increase. By 2200 it will reach 185 persons/km^2. The temperature of the lower atmosphere will increase 0.8°C, and this will lead to a rapid growth of vegetation (217 tons/km^2 in 2200). When $t > 2200$, existing food production rates will start to limit human population growth. Mineral energy sources will become the limiting factor after 2300. Consequently, even if existing development rates for contemporary /46
human society are maintained in the biosphere, acceptable conditions for human existence will continue for at least the next 250 years. During this period, mankind must first solve the problem of establishing an equilibrium with the environment and discover new energy sources.

Now let's have a look at some hypothetical situations which might arise in the future. Figure 3 shows the results of a simulation which presupposed that by the year 2000 both regions will halve pollution generation rates, non-renewable resource expenditure will be reduced 50%, nekton harvesting will drop 10%, agricultural capital will increase up to 45%, and capital investment $U_{Rg} = U_{RG} = 10\%$ and $U_{\zeta g} = U_{ZG} = 5\%$. By 2000, 80% of the land area suitable for farming will be utilized, animal husbandry productivity and P/B -- the coefficient of agricultural vegetation -- increase 1.5 and 4 times, respectively, relative to 1970 levels, and values for T^*_ζ, T^*_Z, and T_G decrease 30%.

In this case, apparently, the system enters a quasi-stationary mode where population density fluctuates from 50-200 persons/km^2. Either CO_2 or food become the limiting factor at various stages. Non-renewable resources become limited after the year 2300. If mankind succeeds in switching to a new level of resource utilization by then, the "catastrophe" will be averted.

Model calculations indicate that the worst gaseous conditions in the atmosphere may set in by 2070, if coordinated inter-region management is not achieved. CO_2 concentration would exceed 0.0748%.

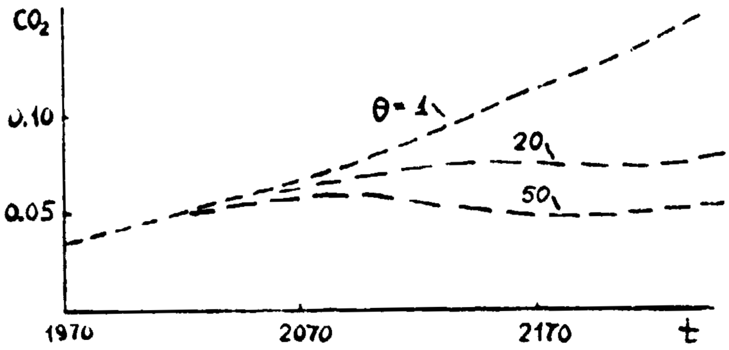

Fig. 4. Changes in atmospheric CO_2 concentration when there is a discrepancy in natural resource utiliztion rates for two biospheric regions. Explanation in the text. Atmospheric CO_2 concentrations are expressed in percents.

The model we examined here, as preliminary calculations have demonstrated, is flexible enough to reflect the natural and anthropogenic processes in the biosphere. It may, therefore, be used to study assorted hypothetical situations in order to find adoptable actions for controlling these processes. /48 Allowance for regionality in the model may make it possible to evaluate the role of the regions in the fate of the biosphere. Specifically, fig. 4 shows the dependence of atmospheric CO_2 concentration on the relationship between initial regional component conditions, with the assumption that region 1 implements measures to conserve the environment and region II retains the same rate of affecting it. Only if $\theta \geq 50$ can region II independently adopt measures to maintain a CO_2 concentration within 0.04%.

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