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GENESIS AND GEOGRAPHY OF SOILS

Spatial and Temporal Evaluation of Plant Production as a Soil-forming Factor

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Abstract—A correlation has been found between the annual plant production and the energy equivalents of heat and water supply. The combined effect of natural and anthropogenic factors on the plant productivity of steppe ecosystems in the Holocene has been evaluated. These results ensure the phytocenotic unit in the mathematical model of the zonal soil-forming process.

It was revealed previously [9] that the general model structure for the changes in the thickness of the humus horizon of automorphic soils ($H(t)$, mm) over the Holocene (t, years) can be represented by the following analytical expression:

$$H(t) = ag\left(\frac{Z(t)}{F(t)}\right)^c \exp(jQ(t))(1 - k\exp(-rt)), \quad (1)$$

where $Q(t)$ is the consumption of energy for soil formation (according to Volobuev [2]); g is the coefficient accounting for the particle-size composition of soil-forming rocks; $Z(t)$ and $F(t)$ are the time-distribution functions of the real (with consideration for anthropogenic effects) and zone-dependent plant productivity, respectively; and a, c, j, k, and r are the empirical constants.

The quantitative evaluation of the synthetic indices, which describe the role of climate and plants in soil formation during the Holocene, is an important and integrated problem in the simulation of the soil-forming process.

The zonal structure of landscapes existing in the Holocene predetermined the integration of spatial and temporal manifestations of phytocenogenesis as the original quasi-climax plant communities with a determined annual level of autotroph-produced organic matter. The use of the synthetic indices, which combine the parameters of heat and water supply, is promising because of the relationship between the primary productivity of phytocenoses and many environmental factors (primarily, climate).

General dependences (without their analytical expressions) were successfully established between the annual increment in the phytomass of zonal landscapes and the hydrothermic potential (the ratio of the total moistening to the radiation balance, R, corrected for the duration of the vegetation period) [13], between the net primary production and R to the latent evaporation heat ratio at the evaporation of annual precipitation ([3, 4], Reimank, 1976, cited from [11], p. 47), between the productivity and the ratio of the potential evaporation to the total precipitation [5], and between the productivity and the product of the sum of temperatures exceeding 10°C (expressed in hundreds of degrees) by the moistening coefficient [7].

An approach proposed by Zubov [6] relates the productivity with the consumption of heat for evaporation and the proportion of the radiation balance maintaining evaporation

$$F = 0.42LE_v^2/R_v, \quad (2)$$

where F is the plant production (t/ha per year); L is the latent evaporation heat; E_v is the evaporation during the vegetation period, g/cm^2; and R_v is the radiation balance of the vegetation period, kcal/cm^2.

In the 1970s, Lieth revealed the pair correlations of the net primary productivity F with the average annual air temperature T and precipitation P [14]:

$$F = 3000\{(1 + \exp(1.315 - 0.119T))^{-1} \times (1 - \exp(-0.000664P))\}. \quad (3)$$

where F is expressed in g/(m^2 year).

The authors of the ARP II model (*atmosfera–rastenie–pochva*, atmosphere–plant–soil) [10], which was developed to study the behavior of the atmosphere–plant–soil system, rightly noted the disadvantages of the models described by (3). Thus, model (3) suggests an increase in annual productivity with increasing temperature at stable precipitation for the ecosystems of the arid zone. The developers of ARP II performed the approximation of results using a regression equation with an expert Lieth's correction for the sign of the productivity change under the effect of the climate for each type of ecosystem.

Volobuev presented a more justified description of the heat and water supply for the zonal complexes of soil and plant communities. Developing the bioenergetic approach, he obtained the relationship between

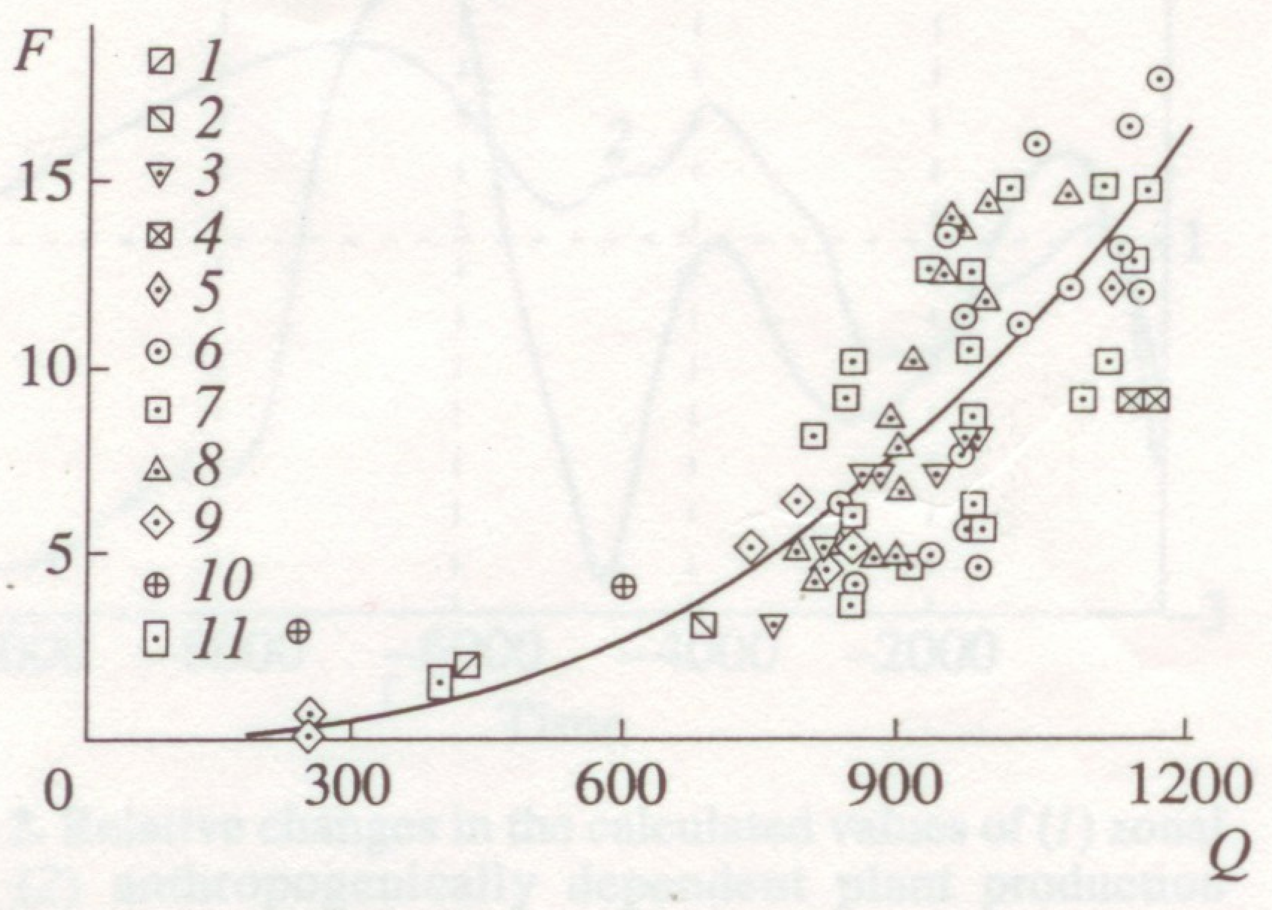

Fig. 1. Dependence of the net primary production of main phytocenoses (F, t/ha per year, in dry weight) on the consumption of energy for soil formation (Q, MJ/m^2 per year): (*1*) Arctic tundras, (*2*) forest-tundras, (*3*) taiga forests, (*4*) mixed forests, (*5*) broad-leaved forests, (*6*) meadow steppes and steppe meadows, (*7*) mixed grass–fescue–stipa steppes, (*8*) fescue–stipa steppes, (*9*) wormwood–cereal steppes, (*10*) semideserts, (*11*) halophytic deserts.

the zonal indices of phytoproductivity (V, t/ha per year) and the total and "climatic" consumption of energy (Q and Q_c, respectively) for soil formation [2]:

$$V = 0.06(Q - Q_c)^3$$

or

$$V = 0.06(R\exp(-1/2.13K) - R\exp(-1/K))^3, \quad (4)$$

where K is the annual factor of relative moistening, and R is the radiation balance. The exponent (2.93–3.00) was calculated as the average of the values for 11 types of terrestrial vegetation, which varied from 1.7 (savannas and semideserts) to 7.8 (tundras).

It should be noted that more extensive data on the plant productivity and the knowledge of their relationship to the zonal and regional climatic indices are required to justify the exponent value.

We analysed data on the annual increase in net primary productivity for the zonal phytocenoses of the Russian Plain, Central Kazakhstan, and the south of Western Siberia based on a number of summarizing works [1, 6, 12], regional studies, and our investigations conducted in the northern Black Sea coastal steppes from 1981 to 1991 [8]. The estimates of the annual increase for 11 types of vegetation ($N = 70$) depending on the corresponding climatic conditions (R, P) are given in Fig. 1. The dependence of the average annual plant productivity (in dry weight; F, t/ha per year) on the consumption of energy for soil formation (Q, MJ/m^2 per year) can be described by the following equation:

$$F = 8.7\times10^{-8}Q^{2.69}, \quad \eta + t_{05}S_\eta = 0.85 \pm 0.13, \quad (5)$$

where η is the correlation ratio, S_η is the error of its determination, and t_{05} is the Student criterion at a significance level of 5%.

Substitution of Q calculated according to Volobuev in equation (5) and its expression in CI units give

$$F = 2\times10^{-3}\left\{R\exp\left(-18.8\frac{R^{0.73}}{P}\right)\right\}^{2.69}, \quad (6)$$

where R is the radiation balance, kcal/(cm year), and P is the total precipitation, mm.

The resulting dependence of the annual productivity on the climatic features made it possible to describe the main stages of natural and anthropogenically induced evolution of the plant cover of the Russian plain by the curves of relative fluctuations of productivity during the Holocene. Because of different trends in the variations of temperature and precipitation observed between the territories located to the north and those to the south of 50° north latitude, we plotted two curves for the changes in Q values over the last 10 000 years, which revealed predominantly simultaneous, low-frequency climatic variations (in energy equivalents). The values of periodical changes in plant productivity over the Holocene calculated by equations (5) and (6) can be described mathematically by means of harmonic analysis. Thus, the relative variations in the annual plant productivity of the forest-steppe and steppe zonal ecosystems over the last 6000 years (i.e., after the climatic optimum of the Holocene) can be approximated by the following Fourier series:

$$\Delta F(t) = \sum_{k=1}^{7} A_k \sin(k\tau + f_k) + 0.72, \quad (7)$$

where $\Delta F(t)$ denotes the relative variations in plant productivity, t/ha per year, about the current annual productivity level of 7.7 t/ha taken equal to 1; τ denotes the time references given by $\tau = 0.105(60 - 0.01t)$, where t is the date on the absolute time scale, years (from 6000 years ago to 0); and A_k and f_k are the amplitude and phase of harmonics k: $A_1 = 0.81$, $A_2 = 1.99$, $A_3 = 2.18$, $A_4 = 1.20$. $A_5 = 0.66$, $A_6 = 0.52$, $A_7 = 0.08$, $f_1 = 1.57$, $f_2 = 1.57$, $f_3 = -0.37$, $f_4 = -0.18$, $f_5 = -0.82$, $f_6 = -0.43$, and $f_7 = -2.99$. Model (7) does not contradict the used set of experimental data, which is confirmed by the values obtained for the coefficient of correlation between the empirical and calculated values (0.85 ± 0.27) and the relative normalized error, y, that evaluates the width of the error band ($y = 0.26$; for a near-functional relationship, $y = 0.22$). The ratio of the annual production of steppe ecosystems to the current level for the main chronological intervals of the Holocene (years ago) was the following: 0.96, 0–600; 1.22, 601–1700; 0.74, 1701–2700; 1.29, 2701–4000; 0.75, 4001–5200; 1.50, 5201–6900; 0.57, 6901–10 000.

The correction for the anthropogenically induced changes in productivity over the historical and ecological periods [8] allowed the quantitative description of

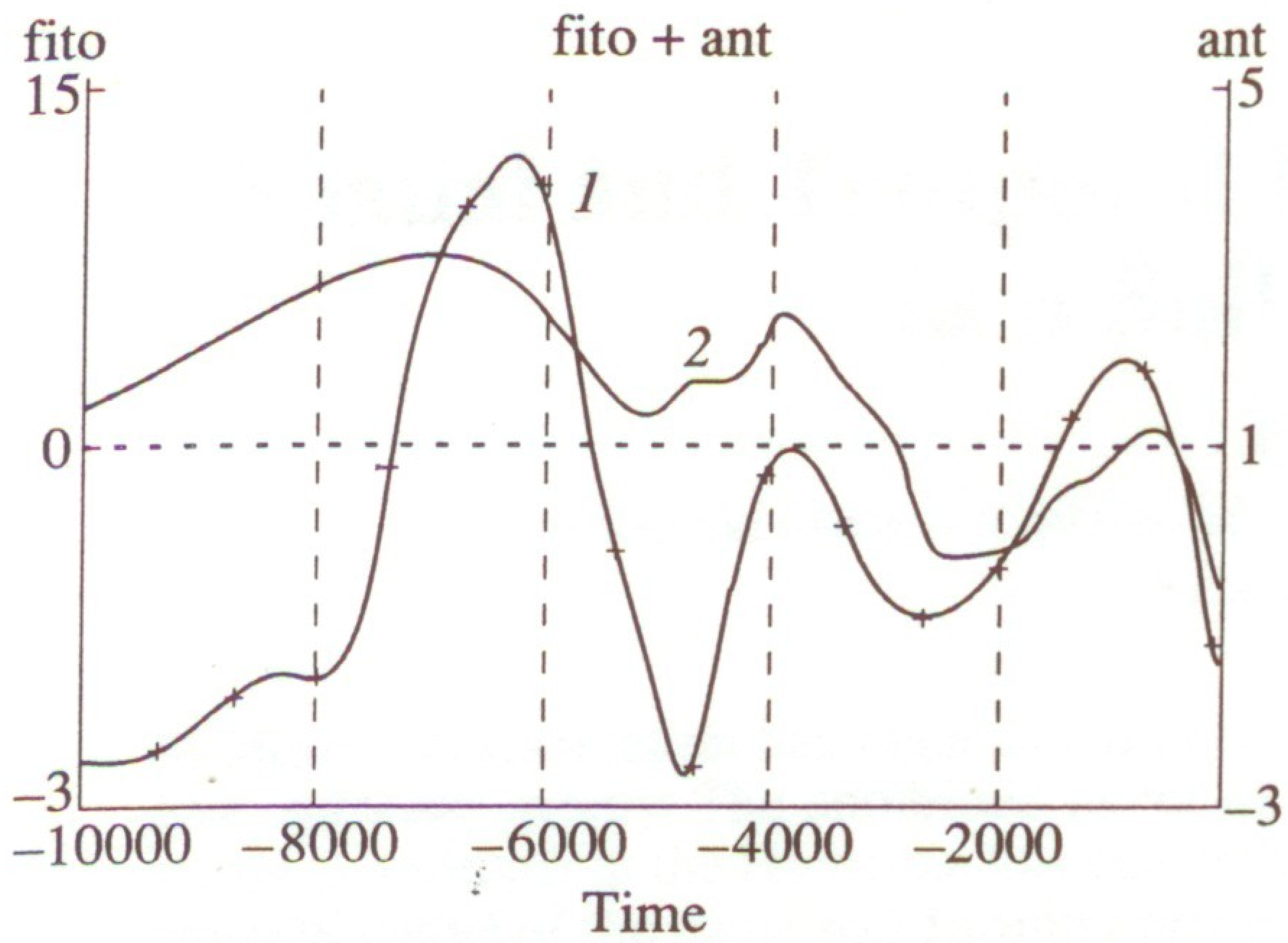

Fig. 2. Relative changes in the calculated values of (*1*) zonal and (*2*) anthropogenically dependent plant production (*F*, t/ha per year) in the Eastern European steppes over the Holocene.

syngenetic evolution of the Eastern European steppes over the Holocene (Fig. 2):

$$Z(t) = 2t^{0.13} + A_0 + \sum_{k=1}^{7} A_k \sin(k\tau + f_k), \qquad (8)$$

where $Z(t)$ is the naturally and anthropogenically determined plant productivity, t/ha per year, $A_0 = 1.02$, $A_1 = 1.95$, $A_2 = 0.80$, $A_3 = 1.33$, $A_4 = 0.47$, $A_5 = 0.38$, $A_6 = 0.18$, $A_7 = 0.09$, $f_1 = -3.03$, $f_2 = 1.57$, $f_3 = -1.62$, $f_4 = -0.74$, $f_5 = -0.26$, $f_6 = 0.48$, and $f_7 = 0.89$.

CONCLUSIONS

(1) Natural and anthropogenically induced fluctuations in plant productivity over the last 10 000 years can be adequately described on the basis of calculations of energy consumed for soil formation.

(2) The phytocenotic unit (conjugated in the mathematical model with the spatial and temporal changes in thickness of the humus horizon of automorphic soils) must include the function of time change in the productivity of zonal ecosystems, which reflects the periodicity of climatic processes and anthropogenic effects. The potentialities of harmonic analysis ensure the solution of this problem.

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