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Quantitative Substantiation of Pedogenesis Model Key Components

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ABSTRACT

The presented structure of humus soil horizon formation model in time for automorphic conditions includes all the factors of soil formation (except for relief). The maximum thickness of humus soil horizon is justified in terms of its dependence from climatic energy costs on soil formation and the characteristics of parent rock granulometric content (expressed in terms of particle content lesser than 0.01 mm). This allows to predict the trends of pedogenesis and speed of humus horizon soils formation in relation to global climate changes, the age of which makes a centry or more than a century.

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INTRODUCTION

The founder of genetic soil science V.V. Dokuchaev [1] showed by soil-forming factors doctrine that each of the genetic soil types reflecting the environment has the potential to evolve in a state of relative equilibrium with a combination of soil-forming factors that characterize stably the corresponding landscape area or a part thereof. Therefore, within flat terrain macroforms (automorphic conditions) the regular change of soil morphological structure is determined primarily by bioclimatic (bioenergy) potential of landscape zone, by the properties of the parent rock and soil formation period. To estimate the contribution of the climatic factor in pedogenesis it is rational to attract the characteristics that define "soil climate" and also bioclimatic factors that influence the soil forming process via biota.

The region which is favorable for the latitudinal zonation of soils and vegetation study is the East European Plain (the area of which makes about 4 million km2): it includes 8 natural areas and more than 30 provinces within these areas. The paper [2] provided climatic substantiation of soil-geographical zoning general pattern of the area concerning the reduction of humus-accumulative process to the north and to the south of forest-steppe zone. In particular, it was shown that within a zonal aspect the dependence of soil profile power from the dryness index has a shape close to parabolic one. A similar kind of dependence is presented in another paper [3], where the connection of humus soil horizon from the annual amount of precipitation (in the range of 300-1700 mm) and hydrothermal coefficient is set. However, it should be noted that these as well as many other complex indicators, not to mention the more simple characteristics of heat and moisture provision within landscaped areas, present the zonal parameters of humus profiles relation with a synergistic effect of hydrothermal factors, especially for the marginal zones of their change amplitude. This disadvantage may be prevented by using a bioenergetic approach [4], which used specifically non-linear representations of bioclimatic relationships. Using the annual value estimates of radiation energy consumption on soil formation (Q) they managed to develop [5] a unified bioenergy system of communities (paragenetic species of soils and vegetation), which demonstrated as a whole the cause-and-effect relations of landscape zonal shifts on the earth's surface. Thus, within the major parts of the East European Plain the latitudinal zoning is caused by the action of various prevailing differentiation factors: in the northern part (taiga and forest region) where precipitation exceeds evaporation value it's the thermal factor and in the southern part (with semihumid and semiarid climate) it's the dampening factor.

For modeling purposes, the process of soil formation in addition to assessing potential climate It is necessary to consider the characteristics of source rocks, especially their granulometric content and soil formation period (soil age). Physical clay fraction plays a special role in soil granulometric content (<0.01 mm), which concentrates 95-100% of humus and clay minerals. There were [6] attempts to identify the dependence of different particle classification (clay (<0.002 mm) and silt (0.002-0.02 mm)) on soil age (up to 14000), using various types of chronofunctions.

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Methods:

In order to determine the dependence for all zonal soil types of the East European Plain of empirically determined humus horizon limit values from climatic potential, we summarized the data of numerous soil surveys. They contained explanatory texts and tabular data for soil maps that were developed as the result of large-scale state soil surveys on individual land-use. From these sources the sample of maximum (extreme) humus horizon power (N_{lim}) for main types of automorphic soils on unconsolidated soil making rocks for individual grades of granulometric content (n=215). At the greatest possible degree of approximation the soil habitats were characterized by heat and moisture provision parameters from the long-term series of climate observations for the nearest weather stations. According to reference data and cartographic materials (only in difficult cases) the heat provision characteristics were determined for all points (radiation balance or the sum of temperatures above 10 °C) and the average annual amount of precipitation.

The radiation balance of the active surface as a leading component of the heat balance determines the amount of heat emission in the air and soil. The ranges of radiation balance on climatic isoline maps were unsuitable to reflect regional differences in thermal provision. Therefore more detailed background data on the annual value of the underlying surface radiation balance for actinometric stations were used. However, its amount was limited for the specified territory. Thus, we used the temperature mode info, which is summarized in the form of agroclimatic zoning diagrams separate administrative areas. At the absence of direct observations for radiation balance (R) components, the use of R dependence from the amount of active air temperatures above 10 °C ($\Sigma t > 10$ °C) became possible. This dependence was obtained for the flat part of the East European Plain [7]:

$$R = 41.87\left[0.0121\left(\sum t > 10^{\circ}\right) + 9.9289\right], \quad (1)$$

where R - the radiation balance, MJ/(m^2•year).

To calculate the energy costs of soil formation in a space point (Q, MJ/(m^2•year)), one may use the results of the mean annual observations made by weather stations concerning such parameters as the annual amount of precipitation and the radiation balance value. When we introduced to the author's formula [4] the multipliers converting the radiation balance values into the international system of unit measurement (conversion of calories into joules), the calculation formula for Q, MJ/ (m^2•year) value has been modified into the following form:

$$Q = R \cdot e^{\left(-1,23\frac{R^{0,73}}{P}\right)}, \quad (2)$$

where R is the radiation balance, MJ/(m^2•year), P is the annual rainfall amount, mm.

Main part:

The functional relationship between the soil system and the major factors of soil formation, which was marked on a qualitative level by V.V. Dokuchaev [1], H. Jenny [8], should be promoted at the level of pedogenesis process analytical representation, expressed by geographic characteristics and time coordinates. Thus, due to computer simulation capabilities a new analog of Jenny equation was proposed, wherein the condition of the soil system is its initial state function, the input variables, the system and time parameters [9]. Using the Lin equation [10] with some additions, a more appropriate expression of the total change of a soil profile over a pedogenic time period t = t_n - t_0 (where t_n is the current time and t_0 is the beginning of pedogenesis) should be expressed as:

$$S = \int_{t_0}^{t_n} f\left[cl(t), o(t), h(t)\right] dt \Big|_{p(t), r(t)}, \quad (3)$$

where S represents the state and history of a soil, *cl* is climate, *o* is organisms, *h* is human activities, *p* is parent materials, *r* is topography, *t* is time. As previously shown [11] it is possible to use the directed development of morphogenetic processes analogy in automorphic soils throughout the Holocene with the general regularity of growth processes in ecosystems to justify a time function type. Graphically, both processes are represented by S-shaped (sigmoidal) curve. The approximation of this curve type by Gompertz function is the most preferable because of its asymmetry, resulting in greater stretching of the upper branch (the growth attenuation is slow). Therefore, the formation of humus soil horizon (H) in time (t) may be represented as follows:

$$H(t) = H_{\lim} \cdot \exp(-\exp(k + \lambda t)), \quad (4)$$

where H_{lim} is the zonal and provincial level of extreme humus horizon value; λ is the coefficient of process dynamics, which has the reverse time value (1/year); k is the constant.

Provided that the variables (N_{lim}) for region zonal soils are justified (for example, on the East European Plain they make at least 9 of the main soil types), the equation (4) may be graphically represented as a series of curves. It should be noted that the actual values N_{lim} is the reflection of the soil-forming climate potential for the entire Holocene.

Taking into account the dependence of automorphic soil humus horizon (A + AB) power from zonal-provincial resource of heat and moisture provision, the income of vegetable matter, time, and parent rock granulometric content, the total record of change model for automorphic soil humus horizon (*H(t)*, mm) during the Holocene (*t*, years) may be represented by the following formula:

$$H(t) = a \cdot g(PC) \cdot \left(\frac{FM(t)}{Z(t)} \right)^n \exp(j \cdot Q(t)) \cdot \exp(-\exp(k + \lambda t)), \quad (5)$$

where g(*PC*) is the function reflecting the influence of parent rock granulometric content through the physical clay content (the particle size makes < 0.01 mm); *FM(t)* and *Z(t)* are the functions of the actual (including anthropogenic influences) and zonal plant product distribution in time; *Q(t)* is the energy costs on soil formation (according to Volobuev [4]); *a, n, j, k, λ* are empirical constants.

The previous facts demonstrated [12] that during the Holocene the climatic conditions at the East European Plain during the centuries-old regime were periodic ones. Over the past 6,000 years two peaks of influence on soil formation should be noted concerning the climate costs (Q) 4.2-3.4, 1.7-0.25 thousand years ago, when the values of energy costs on soil formation (Q) increased compared to modern conditions at 25-145 MJ(m^2•year); and two minima: 5.5-4.2, 3.4-1.7 thousand years ago, when the Q scores were lower by 55-130 MJ/(m^2•year).

Considering the relevant organization and the material-energy status of soil as the result of its development during the Holocene, it should be noted that the major factors of soil formation have different significance and the strength of their influence on pedogenesis varies with the age or stage of soil development [13].

During the soil self-development the plant habitat change takes place and the processes of relationships within "soil-plant" system determine a gradual vegetation change (productiveness, species diversity, tree waste biogeochemical features, etc.) that actually defines the essence of an autogenous succession [14].

Hyperbolic, polynomial or nonlinear functions might improve not only the fit of the chronofunction but also advance our understanding of the pedologic system [15]. In particular, from the previously mentioned type the S-shaped (sigmoidal) curve, general form of equation: $Y=1/(a+be^{-X})$ [15] in our study of soil and climatic relations the curve of this species was chosen but with other analytical form:

$$Y = Y_{lim} / (1 + \exp(a - bX)) \quad (6)$$

The approximation of the empirical data (Fig. 1) in the values of the extreme humus soil horizon (N_{lim}) power in specific soil and climatic conditions, the energy potential of which is expressed through the Q value (according to equation (2)) made it possible to obtain the following equation

$$H_{lim} = 2000 / (1 + \exp(5.346 - 0.0052 \cdot Q)). \quad (7)$$

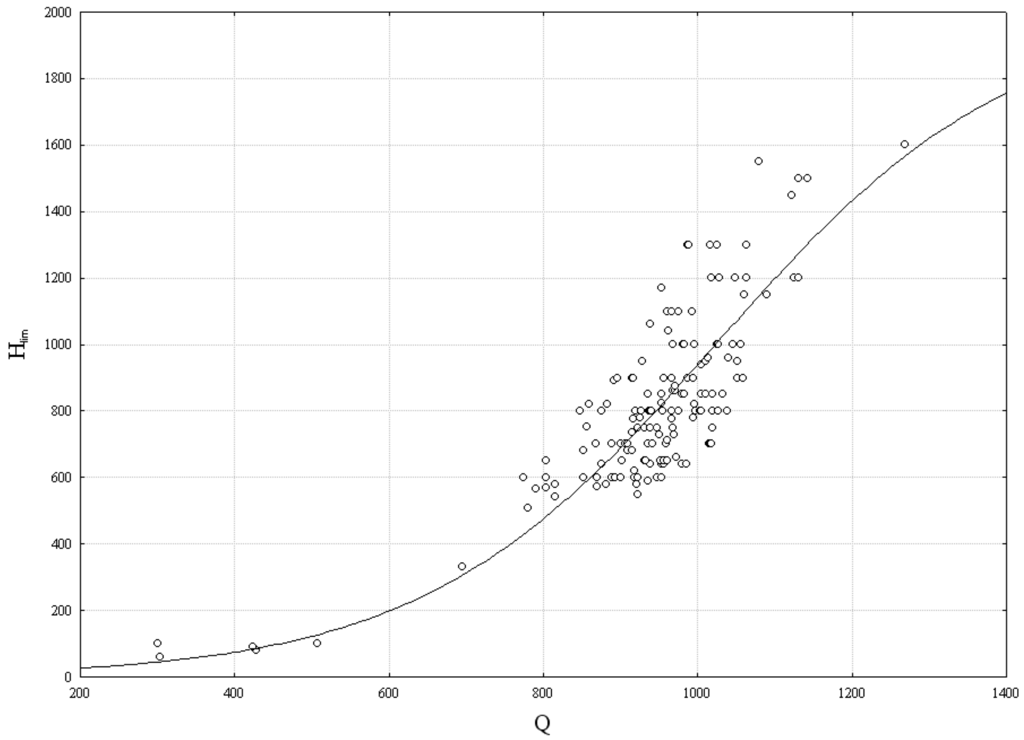

Fig. 1: The dependence of extreme humus horizon (N_{lim}, mm) power for zonal soils of the East European Plain from the energy costs on soil formation (Q, MJ/(m^2•year)).

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Based on thermodynamic concepts, the soil formation is a natural process of substrate energy and thermodynamic characteristics increase. The soils are developed within this substrate [16]. At the development of approaches to the mathematical description of soil formation process it was proposed to determine [5] the amount of energy involved in soil formation, in terms of climatic parameters and the annual growth of water components, which demand experimental data concerning the relative intensity of mineral hydration process in soil forming rocks. The soils of different granulometric composition differ by particle content with a diameter <0.01 mm. The amount of such particles in clay soils makes 61-65%, and the corresponding amount in sandy loam soils makes 21-25%. If the granulometric composition of soil becomes less heavy, i.e. the proportion of < 0.01 mm particles decreases (from 75 to 15%), the thickness of the humus soil horizon increases. This feature represents the dependence of correction coefficient on the granulometric composition of soil (g(PC)) from the composition of particles lesser than 0.01 mm (PC,%):

$$g(PC) = 1.957 \cdot PC^{-0.19}, r = 0.62. \tag{8}$$

Taking into account the equation (8), we obtain the dependence of humus soil horizon (N_{lim}) extreme power from the energy costs on soil formation (Q) and the content of particles lesser than 0.01 mm (PC,%):

$$H_{\lim} = \frac{23914.6 \cdot PC^{-0.19}}{1 + e^{(5.35 - 0.00523 \cdot Q)}}. \tag{9}$$

Graphically the dependence of humus soil horizon (N_{lim}) extreme power from two variables is shown by Fig.2. Thus, when we use such type of soil-formation process of the chronofunction during modeling as S-shaped curve the subjective moment of humus soil horizon power (N_{lim}) value selection may be replaced by calculation procedure of its substantiation based on the particle content lesser than 0.01 mm and the climatic parameters of instrumental period (according to formula (9)), which increases the predictive value of soil formation rate according to model (5).

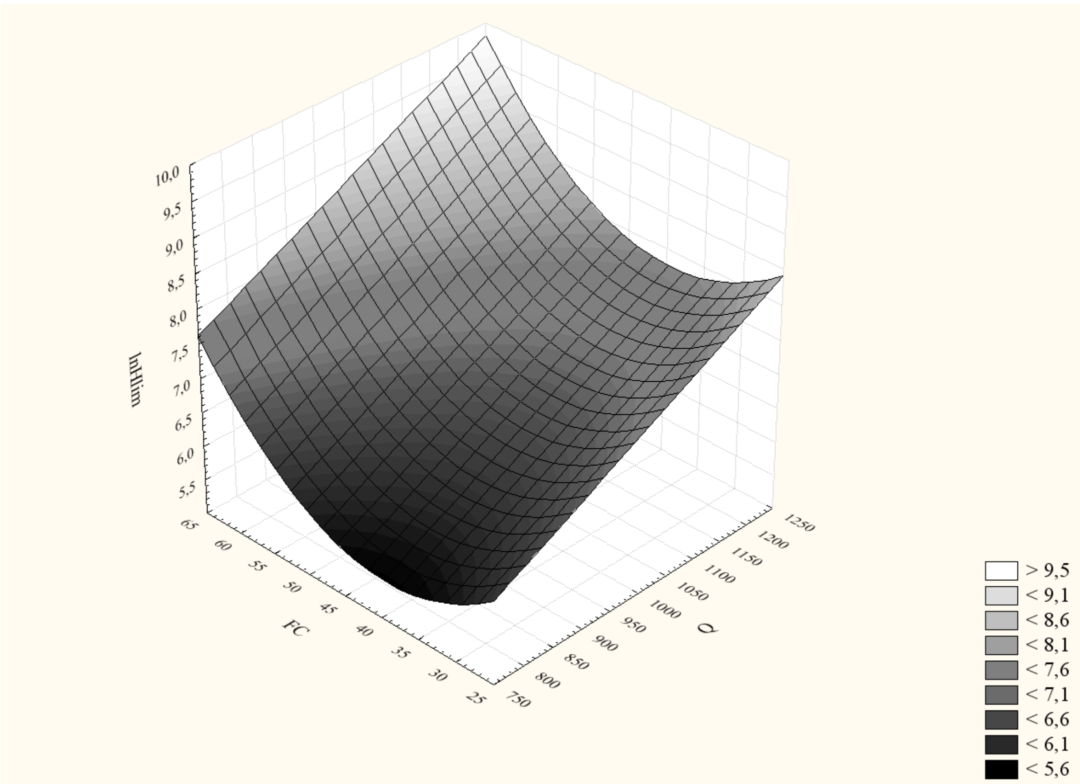

Fig. 2: Dependence of extreme humus horizon power (Nlim, mm) for zonal soils of the East European Plain from energy costs on soil formation (Q, MJ/(m2year)) and the content of particles lesser than 0.01 mm (%).

Conclusion:

Using ergodicity hypothesis, as the space-time compensatory phenomenon making it possible to conduct similar assessments in space by the estimates in time and vice versa, the dependence of the humus horizon extreme power from energy costs on soil formation allows us calculate the development extreme values that a soil of particular granulometric composition may attain provided the keeping of continuing climatic conditions of the modern era (instrumental period), taking into account the long-term climate scenarios, either by past time intervals (if the results of climate reconstructions are available).

Summary:

The results of empirical data large array processing about the maximum parameters zonal soil humus horizon (A + AB) and their respective conditions of heat and moisture provision in eight landscape zones of the East European Plain allowed get a general analytical expression of humus horizon extreme power with the energy costs on soil formation. Subject to representation of variations concerning granulometric composition of source rocks through the particles with a diameter lesser than 0.01 mm we were able to determine the energy potential of the combined influence of climate and granulometric composition on humus horizon extreme power formation. This provides possibilities for modeling and evaluation of pedogenesis trends and the potential rate of humus soil horizon formation for long-term climate scenarios of biosphere future development.

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