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GENESIS AND GEOGRAPHY OF SOILS

Towards "New Soil Geography": Challenges and Solutions. A Review

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Abstract—This paper provides a review of the current state of soil geography and budding directions for the development of pedogeographic research. We mention some new ideas in the frames of structural approach rooting in the classical concept of soil cover pattern and based on new concepts, such as pedodiversity assessment, graph theory, and geostatistical analysis of soil spatial variation. We note the significance of digital soil mapping in the development of the theory and practice of pedogeography and stress that digital soil mapping is a method that cannot replace soil geography as a scientific discipline. There is a need for deeper integration of mathematical methods in traditional soil geography. We stress that pedogeographical models are required for predicting soil properties and regimes even in digital agriculture. We discuss the necessity for adequate reflection of polygenetic soils in the soil mantle, and recommend using both indirect paleogeographic information and current remote and proximate sensing data. We also note the difficulties in predicting the spatial distribution of anthropogenically transformed soils using state factor theory; we discuss the possibilities of broader use of historical and economical geography data. In conclusion, we suggest developing "new soil geography" not only through integration of mathematical methods but also through closer integration with allied sciences.

Keywords: soil cover pattern, pedometrics, polygenetic soils, anthropogenically transformed soils, digital agriculture

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INTRODUCTION

A fundamental challenge of soil geography is to analyze the causes of soil heterogeneity, to map and predict soil properties in geographic space, and to create geographic pedogenetic models. To effectively predict the spatial distribution of soils, we should know the regularities controlling it. In recent years, it has been noted that we should also take into account the organization of the soil cover at a level, which cannot be analyzed from the point of view of deterministic logic because of the lack of data, as well as the pseudo-stochastic component of soil variability [71]. Accordingly, contemporary soil geography requires a deeper understanding of the geographical regularities that determine spatial patterns of the soil cover at different levels of its organization. This understanding should be harmoniously combined with a system of mathematical methods of spatial modeling. In this paper, we try to assess how much such a synthesis is possible within the framework of the traditional soil-geographic paradigm. We also consider the prospects for the refinement of this paradigm, at least at the level of new formulation of the usual ideas. Until recently, the development of statistical analysis of the spatial heterogeneity of soils, geostatistics, and other methods of spatial modeling and digital soil mapping (DSM) was weakly linked with the theoretical foundations of soil geography. At the same time, it should be noted that the DSM concept has greatly stimulated interest in soil-geographical research, since DSM requires knowledge of quantitative relationships between the spatial distribution patterns of soil forming factors and soil properties [70].

Our tasks go beyond discussing the integration of mathematical methods into traditional soil geography and the quantitative revolution [45] in the geography of soils. The analysis of the tasks that are currently ripe in this field of science has led us to the idea that the methodological apparatus of soil geography needs a revision; modern pedogenetic concepts, including the concept of soil memory and the concepts describing the anthropogenic impact on the soil cover should be integrated into the theory of soil geography.

APPROACHES TOWARD CHARACTERIZATION OF SOIL-GEOGRAPHICAL SPACE

The distribution of soils on the surface of the Earth can be explained in different terms. Considering the totality of soil-geographical studies, we should acknowledge that they are very heterogeneous in scale, the systems of applied methods, and terminology. The practical tasks of soil geography are also diverse: mapping at different scales, soil zoning, data extrapolation and interpolation, etc. From the point of view of epistemology, these tasks imply totally different mental operations, such as synthesis, analysis, classification, generalization, etc. It is evident that it is almost impossible to integrate the entire diversity of soil-geographical concepts allowing us to solve these problems into a single methodological approach. Goryachkin [9] emphasized the importance of the theory of soil cover patterns developed by Fridland [44] and noted that there are other approaches in soil-geographical research [11]. We agree that the description of the organization of the soil cover is an important but not the only possible approach in soil geography. In our opinion, it is possible to distinguish between three different approaches in the geography of soils. These approaches differ in the system of concepts, terms, and methods applied to soil cover [23]. They may be called the static (or the steady factor) approach, the dynamic approach, and the structural approach. These approaches in soil geography do not exclude one another; they are mutually complementary. The steady factor approach originates from the works of Dokuchaev [14]. It is based on the spatial application of the factor–profile paradigm developed by Dokuchaev. The major idea of this approach as expressed in a somewhat vulgar form is that the soils on the Earth are different, because the factors of soil formation and their combinations vary in space. Basic precepts of the factor approach are clearly expressed in the "bioclimatic" laws of the latitudinal and vertical zonality of soils. The term static approach does not mean that dynamic pedogenetic processes are not taken into account. By definition, any soil is a dynamic natural body. The static nature of this approach is that it implies the formation of soils in a relatively stable field of the factors of soil formation (steady-factor approach); this approach does not draw attention to lateral flows of matter that differentiate soil cover; in other words, only vertical processes in the soil profile are considered [75].

The dynamic approach is aimed at explaining the processes responsible for the differentiation of soil cover: it implies the interpretation of soil cover in terms of soil-differentiating processes, that is, it considers the lateral flows of matter in solid and dissolved forms. Within the framework of this approach, the origin and evolution of soil combinations are considered. The dynamic approach includes many specific areas and concepts, some of which are discussed below. The ideas of soil geomorphology that studies the role of slope and erosion processes in the formation of soil cover are in the domain of dynamic approach. In a broader sense, soil geomorphology associates the distribution of soils with the relief; in particular, within the framework of the catenary approach. Soil geomorphology in a broad sense has been developed in both Russian and western schools of pedology [13, 30, 33, 47, 51, 54, 82], although the term itself is mainly used in English-language literature. In the Russian school of pedology, the lateral differentiation of soil cover as a result of the movement of matter has been studied within the framework of landscape geochemistry [6, 31, 32].

Finally, the third (structural) approach considers the soil cover as a set of objects on the Earth's surface and analyzes their qualitative, semi-quantitative, and/or quantitative characteristics. It deals with the parameters of the soil cover components (the shape and dimensions of the polygons) and their mutual relationships. Although this approach mainly concentrates on the description of soil cover patterns and their characteristics, it does not exclude the subsequent interpretation of the genesis of these patterns; often, this is the main goal of the study. The structural paradigm is most clearly manifested in the theory of soil cover patterns developed by Fridland [43, 44, 53] and in the analogous concept of soil landscapes formulated by Hole and Campbell [59]. A more formal description of the soil cover organization is performed with the use of the methods of pedometrics, including, in particular, special methods for assessing pedodiversity [1, 62, 63, 65, 72]. This approach separates oneself not only from the genesis of soil cover pattern but also from the characteristics of the components of this pattern [21, 24]. An even greater degree of formalization is characteristic of geostatistical methods that consider the spatial distribution of individual quantitative properties of soils [20, 36, 71, 73]. As already mentioned, the three approaches in soil geography are mutually complementary rather than mutually exclusive. For example, on different scales, the same soil landscape can be characterized in terms of a static approach on a small scale and a dynamic approach on a large scale. At the same time, it should be noted that the static and dynamic approaches are not rigidly tied to a specific scale. Thus, soil mosaics (contrasting combinations of soils related to spatial alternation of different parent materials) on a large scale may well be interpreted in terms of the lithological heterogeneity within the framework of the static approach, and soil changes over large (up to thousands of kilometers) distances can be explained within the framework of the dynamic concept of soil geochemical arenas in definition by Glazovskaya [6]. Application of two or more approaches to the study of soil cover allows us to deepen our understanding of the spatial organization of soils. Quite often, the structural characteristics of the soil cover are subsequently interpreted in terms of static and dynamic approaches. Actually, this is the basis of the study of soil cover patterns [43, 44]: soil combinations are classified, among other criteria, according to their genesis.

PROMISING DIRECTIONS OF THE DEVELOPMENT OF SOIL-GEOGRAPHIC STUDIES

The need for revision of the old ideas stems not only from the need to integrate the methods of mathematical modeling and DSM but also from the fact that many ideas, on which soil geography is based, have already been explicitly or implicitly transformed. A historical review of the development of soil-geographical research is beyond the scope of this paper. However, it makes sense to mention some achievements in the field of soil geography in recent decades, as they actually shape the base for a new stage in the development of this field of science.

As noted above, the great achievement of soil geography in the second half of the twentieth century was the creation of the theory of soil cover patterns by Fridland [44, 53] and its further development in the Russian school of pedology [7, 19] and in foreign schools, where it took the form of the analysis of “soil landscapes” [59, 61, 66]. At the same time, the very classification of soil cover patterns turned out to be rather complicated and generally incomprehensible to non-specialists. As a result, it is rarely used outside the Russian soil-geographical school, even in the “light” version by Hole and Campbell [59].

It is interesting to pay attention to the directions that developed after V.M. Fridland. In the Russian school, a number of interesting concepts were advanced by Sokolov [38, 39]. In particular, he argued in favor of the existence of soil areas rather than explicitly expressed latitudinal soil zones. Sokolov creatively understood the catenary distribution of soils from positions of soil hydrology and environmental geochemistry. Special attention to hydrology and its role in the formation of soil heterogeneity was paid by Aparin [3], who developed the concept of hydrological fields of soil formation. An interesting typification of soil cover patterns in northern Russia according to the dynamics of drainage of the territory was proposed by Goryachkin [10]. The specificity of soil cover in forest ecosystems was described in detail by Karpachevskii [16].

Starting from the works of Volobuev [4], many researchers have tried to find a quantitative dependence of the distribution of soils on the earth’s surface on the factors of soil formation at the global level. A somewhat simplified approach was used by Gray et al. [56]. Alyabina [2] developed the concept of soil-forming potential of the environment initially proposed by Gennadiev [5]. This concept was laid in the basis of predictive mapping of soil horizons and soils from data on the bioclimatic conditions and distribution of parent materials.

A fundamentally new and promising approach to the organization of soil cover was proposed by Kozlovskii [18], who introduced the concepts of “internal mass,” “interface,” and “information structure of soil cover.” From our point of view, this approach contains the potential for a capacious formalized characterization of soil cover on different scales. Regretfully, these works did not receive continuation. Those wishing to expand their understanding of theoretical approaches in modern soil geography are encouraged to familiarize themselves with the available reviews [8, 9, 11].

An interesting approach to identifying the sources of the complexity of soil landscape was suggested by Phillips [77]. This approach is based on the method of “spatial adjacency graphs”: the formal indicators of the graphs of spatial conjugation of all soils of a plot (spectral radius) are compared with the set of analogous indicators of empirically selected “factor chains” of soils, e.g., topocatenas, soil sequences differentiated according to the character of parent materials (lithocatenas), etc. If the spectral radii of all “factor chains” turn out to be smaller than the spectral radius of the area, the soil cover cannot by fully explained by known factors. In this case, a researcher sees prospects for further study. Also, graph theory can be used to solve theoretical problems, such as the analysis of the causes of complexity of the soil cover [79], as well as applied problems, such as estimation of possible errors on soil maps [76].

Particular attention should be paid to the methods of formalization of soil-geographical data and their use for a deeper understanding of the genesis of soil cover. First of all, we should mention the concept of soil diversity, or pedodiversity, which is considered a formal indicator of the complexity of soil cover and can be calculated using various indices of diversity (by Shannon–Wiener, Simpson, Jacquard, etc.) and graphic models, by analogy with biological objects [21, 37]. The disadvantage of this approach is a strong dependence on the scale of research and soil classification system [22]. At the same time, the concept of pedodiversity makes it possible to successfully analyze the spatial heterogeneity of soils, its causes, and its relationships with the biodiversity [65]. As previously shown by some authors [64, 80, 81], pedodiversity is closely related to the geomorphological evolution of the entire landscape. In our opinion, the evolution of river network is only a specific case of the soil cover development. Earlier, we assumed that, in general, pedodiversity increases with age up to a certain limit; then, after reaching the maximum, it slowly decreases [67]. A more detailed analysis of the links between soil geography and the concept of pedodiversity can be found in our earlier paper [21].

In recent decades, in parallel with the development of soil geography, a rapid growth in quantitative methods for analyzing the spatial organization of soils has been observed. In the 1970s and 1980s, the mathematical apparatus used in the quantitative prediction of the distribution of soils and their properties expanded: various statistical methods of regression and discriminant analysis were applied [69, 74]. In the 1990s, geostatistical methods became widespread [35, 48, 73]. Geostatistical analysis and modeling reveal the internal patterns of the spatial distribution of soil properties [36]. Spatial variation of soil properties can be defined as a function of three indicators: (1) a range of values that can be modeled from data on soil forming factors; (2) a local variability of indicators, which is difficult to derive from known factors and, therefore, should be modeled on the basis of semivariance depending on the distance between observation points; and (3) stochastic (random) or pseudostochastic variation, which is not modeled in any way and is taken as an empirical constant [55]. It would seem that such an approach leads us to the conclusion that the spatial distribution of soil properties cannot be predicted. However, paradoxically, the abandonment of rigid determinism allows using a probabilistic approach, which has proved to be efficient for solving some practical problems. For example, variogram analysis, or variography, reveals latent periodicity in the distribution of soil properties. In some cases, it helps us to judge the degree of development and disturbance of the soil cover [20]. The autocorrelation analysis allows us to determine the spatial structure of soil indicators: for example, the values of the Moran coefficient show how closely certain values are grouped in space. Interpolation of soil data is used to produce the maps of soil horizons [36] and the maps of taxonomic soil groups [46] that are more familiar to a soil geographer.

The fuzzy logic apparatus became an additional tool for modeling soil cover [52, 87–89]. The development of mathematical methods for spatial modeling has led to somewhat unexpected results: some researchers conclude that these methods are an alternative to traditional soil geography. The possibility that exact mathematical methods supplant inaccurate geographical knowledge [15, 58] is, in essence, the manifestation of positivism in its primitive form [23]. This issue has been seriously discussed in the scientific literature. However, with time, owing to the development of DSM [40, 70], it has become evident that mathematical modeling should be based primarily on expert knowledge. The Working Group on DSM of the International Union of Soil Sciences suggests the following definition: "Digital soil mapping is the creation and the population of geographically referenced soil databases generated at a given resolution by using field and laboratory observation methods coupled with environmental data through quantitative relationships." The rapid development of the methods for processing spatially distributed data and GIS software together with an increase in the quality of remote sensing data have led to a qualitative leap forward in the creation of digital soil maps [29], including maps based on limited empirical field information [88]. In recent years, the scale of application of DSM has expanded: in some papers, modeling has already been considered on a continental scale [57]. The DSM methodology readily absorbs classical approaches to soil geography: for example, the concept of soil cover patterns was successfully integrated into DSM both in the Russian school of pedology [40] and abroad, where it was developed within the concept of pedodiversity [49]. At the same time, it should be clearly understood that the DSM concept does not replace soil geography, since *the method cannot replace fundamental discipline*. However, it sets a new bar for the requirements to soil-geographic models. To a large extent, the requirements of DSM show gaps in a wide range of issues of soil geography. In particular, this concerns our weak ability to take into account soil paleofeatures and the anthropogenic transformation of soils.

POLYGENETIC SOILS IN THE SOIL-GEOGRAPHIC SPACE

As it became apparent in recent decades, the vast majority of soils with a developed profile on our planet have undergone more than one cycle of soil formation, which left corresponding records in them [41, 82, 86]. This, in particular, results in the diversity of soilscapes on the planet. Reconstruction of past soil-forming processes is a difficult task, especially if we want to reveal the spatial distribution of the relict properties in soils. The cartographic reflection of theoretically valid relict features on a small scale was realized by Kovda [17]. Cartographic representation of relict features on a large scale on more detailed maps may partly be based on the reconstruction of the past pedogenesis and partly on the methods of spatial analysis and modeling, which have been developing rapidly in recent decades. For example, the analysis of the spatial variability of the physical properties of gray forest soils made it possible to identify the paleocryogenic structures that regularly manifest themselves in the soil space [12]. Subsequently, the spatial structure of relict soil features was studied in detail by Phillips [78].

The inclusion of these methods in the general structure of soil-geographical knowledge is a new challenge, because the traditional soil-geographical theory was a source of expert knowledge for spatial modeling, though spatial models were rarely applied to the solution of soil-geographic problems themselves [20].

The most important step in the development of the soil-geographic concept was made in the work by Targulian and Sokolov [42] on the concepts of soil-moment and soil-memory. This study posed the problem of the significant role of inherited features in the profiles of modern terrestrial soils. This line was developed in further works of Russian pedologists [84]. A successful experience in mapping paleopedogenic features was presented by Makeev for the periglacial regions of the Russian Plain [27].

Impressive success has been achieved in mapping paleosols and their inclusion in the general scheme of the formation of the soil cover in Italy by Costantini with coauthors [50]. As the soil cover of Italy is very complex, and polygenetic soils and soils on buried profiles predominate in it, the diagnosis of such formations turns into the main pedological problem for this country; remote sensing methods and geophysical surveys have been successfully applied to solve it.

SEARCH FOR THE REGULARTIES OF THE ANTHROPOGENIC TRANSFORMATION OF SOILS

Although numerous works attest to the global nature of the anthropogenic transformation of soils, a full-fledged prediction of the distribution of soils on the planet is usually limited to natural soils reflecting the natural factors of soil formation. At the same time, in the Russian soil-geographical school, maps show real soils and reflect their use in agriculture, either in terms of the degree of soil cultivation, or in the form of "agrosoils." It is obvious that the soils under agricultural use or the soils of settlements differ significantly from their natural analogues shown on the maps. At the same time, the display of the anthropogenic transformation of soils under a long-term (up to centuries-old) fallow on the maps is only possible on the basis of direct field diagnostics [26] or on the basis of additional information (e.g., information from current or historical land-use maps [25]). Although the identification of anthropogenic changes in soils is not an easy task, there are a number of approaches and methods to identify areas that have been under anthropogenic impact in the past on the basis of remote sensing data and terrain studies [28]. More ancient traces of soil transformation can also be diagnosed [60]. At the same time, it should be remembered that traces of the past conventional plowing are gradually erased from the soil profile [26].

We argue that the inclusion of the anthropogenic factor in the general context of soil-geographical works is only possible in close cooperation with other sciences, including humanitarian sciences; above all, history and economic geography. In particular, the spatial distribution of soil degradation processes is associated not only with bioclimatic and geomorphological factors but also with the spatial distribution of industry and agriculture [68].

CHALLENGES OF CONTEMPORARY SOIL GEOGRAPHY AND POTENTIAL RESPONSE TO THEM

While considering current challenges facing soil geography, it is important to answer a fundamental question: how much will soil geography in general be in demand in the near future to solve applied problems in agriculture and related disciplines? It is no secret that the development of soil geography was initiated as a response to the need for land inventory for agricultural purposes and was further stimulated by practical demands [34]. The transition from spatial models on the basis of soil taxa to the mapping of individual soil properties [71] was largely justified by the requirements of precision farming, which is based on the data on each point with given coordinates. Today, the transition from precision agriculture to "smart" and "digital" farming is being declared, which means that the static characteristics of the soil are no longer needed: instead of a map once made in the course of soil tillage or fertilization, a new dynamic cartogram is generated each time on the basis of "big data" obtained from multiple sensors [83]. However, even when obtaining data on the dynamic properties of a soil in real time, for example, using hyperspectral spectroscopy [85], the results are limited to the soil surface. Meantime, to calculate irrigation water or fertilization rates, information on the soil profile is required, and this information can only be obtained from soil-geographic models. This suggests that knowledge of the spatial distribution of soils in the future will be in demand in agriculture. It is also obvious that soil geography has been and will be in demand not only in the agricultural sector but also in other areas of human activity: ecology, climate change studies, paleogeography, etc.

As noted above, one of the challenges of contemporary soil geography is the need to integrate with mathematical models of the spatial distribution of soil properties. To create digital models of soil cover, it is necessary to know the quantitative relationships between soil forming factors and indirect soil characteristics, on the one hand, and soil properties, on the other hand. It is not only about translating the existing knowledge of the soil cover into the language of mathematics but also about the level of our knowledge, which is still insufficient for the quantitative description of many empirical regularities. The situation is aggravated by the fact that the large-scale soil survey has virtually disappeared in most countries of the world and, most likely, its resumption is not expected. In our opinion, the only possible solution under these circumstances is related to the wider use of both proximate sensing and indirect information obtained from multiple sources using the "big data" technology. The development of these technologies allows using huge amounts of heterogeneous and poorly ordered information for modeling the desired characteristics of the soil. Sources of indirect data may be diverse: satellite data; information obtained from drones, including those equipped with hyperspectral cameras; real-time weather data; and many other sources, whose use for this purpose has not been considered yet.

These challenges are associated with the growing need for the reflection and prediction of diverse quantitative soil indicators in the databases and on the maps. Soil geographers have various options to deal with these problems. In particular, a departure from a traditional soil map showing taxonomic groups of soils or their associations as the basis for the geographic analysis of the soil cover is possible. Instead, cartograms of individual soil properties and probabilistic maps of individual soil horizons may be developed [36]. Also, cartograms presenting data on soil processes, functions, and ecosystem services may be created. A separate task is the comparison of data on the taxonomic diversity of soils and the variability of individual soil properties within given soil polygons [35]. We assume that this information may become an important additional characteristic of the soil cover patterns. The spatial heterogeneity of the soil cover in most cases can and should be interpreted from the soil-geographical positions.

The next challenge is the current need not only to reflect the static state but also to predict the dynamics of landscapes, including those under anthropogenic loads, and to assess various risks, including, for example, the risks of soil degradation, crop failure, catastrophic processes, etc. Obviously, this challenge assumes combined use of dynamic models and spatial tools, such as GIS software.

As noted above, the polygenetic nature of most soils makes it difficult to establish a linear relationship between the actual factors of soil formation and the soil profiles. At the same time, there is a need to reflect the real properties of soils that are weakly associated with the current natural factors of soil formation and can be regarded as relict properties. The answer to this challenge may be the identification of paleosols and relict soil features with the use of remote sensing and proximate sensing techniques. In some cases, a regular survey of individual soil properties, including proximate or remote sensing methods, can help us to identify patterns associated with paleocryogenesis or other processes that took place in the past.

Finally, there is a need to reflect the real properties of soils that are weakly associated with current natural factors of soil formation and are totally dependent on the past or actual anthropogenic activities. In some cases, the answer is evident, as the anthropogenic impact is evident in the current type of land use. At the same time, the history of land use is not always obvious. In this situation, the systematization of anthropogenic influences and their allocation to some specific geographical settings may be helpful. Good results can be obtained from historical data on land use in the past.

CONCLUSIONS

The current development of science and the needs of society necessitate the advance of soil geography toward the development of quantitative models describing the dependence of soils and soil properties on the factors of soil formation coupled with more active use of the methods of indirect soil diagnostics. It is a challenge to create new maps reflecting the geographical patterns of certain soil properties, functions, and services in their dynamics.

Actual maps should take into account relict and anthropogenic features that are difficult to predict, but can be identified by advanced indirect methods of soil research, including remote sensing and proximate sensing methods.

The pedological community should formulate the theoretical basis of the “new soil geography” for the purposeful development of knowledge of the spatial structure of the pedosphere. At the same time, the transition to the new soil geography should take place in an evolutionary way, through the integration of the existing soil-geographic paradigm into a changing world. The novelty of the soil-geographical science in the future will be not only in a wider use of mathematical methods and quantitative information. As we see it, the future of soil geography also lies in a closer integration with adjacent sciences, such as paleogeography, history, and economic geography, which should help soil geographers to come to a systems understanding of the functioning of soil cover.

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