ISSN 0147-6874, Moscow University Soil Science Bulletin, 2017, Vol. 72, No. 3, pp. 93–99. © Allerton Press, Inc., 2017.
Original Russian Text © N.P. Kirillova, T.M. Sileova, T.Yu. Ulyanova, S.Yu. Rozov, I.E. Smirnova, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 17: Pochvovedenie, 2017, No. 3, pp. 3–10.

SOIL GENESIS AND GEOGRAPHY

Digital Large-Scale Soil Parent Material Map of Chashnikovo Training and Experimental Soil Ecology Center, Moscow State University

N. P. Kirillova*, T. M. Sileova, T. Yu. Ulyanova***, S. Yu. Rozov****, and I. E. Smirnova*******

Department of Soil Science, Moscow State University, Moscow, 119991 Russia
**e-mail: npkirillova@yandex.ru*
***e-mail: tmsileova@yandex.ru*
****e-mail: ulyanova_tatyana@mail.ru*
*****e-mail: watcher008005@yandex.ru*
******e-mail: i.e.smirnova@mail.ru*
Received January 18, 2017

Abstract—A large-scale digital map of the soil parent materials has been produced for the territory of the Chashnikovo Training and Experimental Soil Ecology Center (TESEC), which has an area of 338.9 ha. The digital processing methods for extensive field data (748 sampling points) included incorporation of the data into databases, automated algorithms for soil taxa identification, and various digital soil mapping techniques. The five methods used to produce the map give similar values within an overall accuracy range of 0.69–0.74. The objective sample color criteria in the CIE L*a*b* system were used to identify soil parent materials. Eleven main parent material types have been distinguished; the distinct pattern of their distribution over the terrain relief, which determines the soil diversity in the study area, has been identified.

Keywords: digital soil map, database, CIE L*a*b*, soil color, soil taxa

DOI: 10.3103/S014768741703005X

INTRODUCTION

Soil parent materials are an important factor in soil genesis. The existing *SCORPAN* model based on the scheme proposed by V.V. Dokuchaev [14] most fully reflects the factors determining soil properties at any specific point: $S = f(s, c, o, r, p, a, n)$ with s being soil; c, climate; o, organisms; r, relief; p, parent materials; a, age; and n, territorial neighborhood.

Most studies (76%) use one or two parameters out of the seven for this model. According to an estimate dated 2009 [16], the contribution of soil parent material was only 6%. Such a low value is determined by objective difficulties: geologists use lithologic maps produced by themselves as the main data source [15], while the number of such maps, especially large-scale ones, is limited.

Meanwhile, soil parent material data can be collected during field studies to produce large-scale soil maps. These data, however, have not been incorporated into an integrated system (database), nor did they have GPS coordinates, thus making impossible to use information from field journals collected for specific areas in past decades. The situation changed drastically with the progress of digital technologies and the introduction of GPS into field studies.

Since 2012, Moscow State University's Department of Soil Science has been running the project "Digital Soil Map of Chashnikovo Training and Experimental Soil Ecology Center (TESEC)" for student summer training in field soil cartography [9]. The project meets all the requirements for compiling a digital soil parent material map: (1) all data are incorporated into a database, (2) the soil profile sections have GPS coordinates, and (3) the format of annual studies in the same area makes it possible to define the boundaries of soil parent materials more accurately.

The aim of this study was to produce a large-scale (1 : 10000) digital map of soil parent materials for the territory of the Chashnikovo TESEC based on data collected in the project.

MATERIALS

The TESEC territory is located in Solnechnogorskii region of Moscow oblast, in the southern part of the Klin–Dmitrov Ridge.

The relief was formed by a glacier of Moscow's age. The ancient forms were transformed by subsequent processes. The rolling–undulating character of the relief reflects a moraine landscape at various denudation stages. The hydrological network consists of the Klyazma River and its tributaries, which have formed a ravine–gully network. The area consists of slope spaces combined with terrace fragments represented by leveled spaces. The slopes are trenched with ravines and gradually change into a floodplain occupying an ancient glacial hollow with a chain of limnic widenings filled with peat. The slopes adjacent to the floodplain have specific soil genesis features and have been designated a separate geomorphologic district. The slopes and ravines are mostly oriented towards northeast; their angles vary from 1°–5°. Therefore, the territory is divided into four geomorphologic regions: slopes and terraces, ravines, slopes adjacent to the floodplain, and the floodplain.

Spruce and broad-leaved forests predominate the plant cover. A considerable share of soils are either plowed or have been recently withdrawn from agricultural use. On the floodplain and on slopes adjacent to it, irrigation canals have been laid.

The diversity of soil genesis factors, including relief and soil parent material as primary, results in considerable differentiation of soils in the area. The slopes feature zonal soil types: podzolic and swamp–podzolic soils on covering loams often underlain by moraine and fluvioglacial deposits. In ravines, gullies, and lower parts of the slopes, soddy, soddy gley, and swamp soils on deluvial deposits had been formed. In accumulative conditions, at ravine outlets to the floodplain, deluvium may be combined with peat. The floodplain features a range of alluvial soil types on alluvium and peat. Overall, a relatively small area hosts the entire range of soils typical for similar landscapes [8].

Eleven parent material types have been distinguished in the study area. A soil-forming or parent material means the rock material that the soil is formed from [12]. If it is binomial, the upper soil horizons are formed from one rock material, while the lower horizons are formed from the other. Below is a brief overview of the main soil parent materials present in the study area and their identification features used in field descriptions.

Overall, the soil parent material belongs to the Central Russian mineralogical province [2]. It is necessary to keep in mind the genetic affinity of different deposits, because all of those originate from the transfer of granitoid materials from Fennoscandia by the glacier [4]. The covering loams, moraine, and fluvioglacial sediments are eluvial deposits; deluvial and alluvial sediments, secondary to eluvial deposits, have similar mineral composition because their formation is linked with washout and resedimentation of eluvium of primary glacial rocks.

Here we characterize in the most general terms the mineral composition of the soil parent materials in the study area. According to [3, 12], the following SiO_2 groups are the main light minerals of coarse fractions (>0.01 mm) for rocks of the Klin–Dmitrov Ridge: quartz, chalcedony, and opal (70–80%). The rest consists of feldspars: orthoclase feldspar, potash feldspar, and acid plagioclase. The share of heavy minerals in the deposits does not exceed 1.5–2%. Their composition is homotypic: nontransparent ore and ferruginous minerals, epidote, hornblende, biotite, and garnet. The share of accessory minerals (rutile, tourmaline, staurolite, sphene, and zircon) is insignificant. Finely dispersed minerals of silt fractions are represented equally by kaolinite (with chlorite), illite, and smectite [13]. Obviously, there are subtle mineralogical differences in individual profiles and horizons.

Covering loams of the study area are loess sediments. These are grayish brown; their grain size composition is light loamy with predominant sandy loam fraction (0.01–0.05 mm) whose content reaches 40–50%. Covering loams cover slopes and terraces with a mantle. Normally, their depth is 60–80 cm; covering loams are underlain by moraine or fluvioglacial sediments. Sometimes their depth reaches 1.5 m; in such cases, we believe that the soils formed on homogeneous deposits.

Moraine deposits belong to the marginal zone of Moscow age moraine. Their characteristic feature is a clear reddish hue. Fine earth is sandy, and the share of silt fractions is low; they mostly belong to heavy clay loam materials in grain size composition. Concurrently, the presence of grains >1 mm and boulders are typical. The moraine deposits underlay the covering loams materials and do not crop out.

Fluvioglacial sediments consist of unsorted polymineral sand often cemented with iron hydroxides. Grains >1 mm are present. Such dense layers may act as an aquiclude. Fluvioglacial sediments rarely appear as a homogeneous soil parent material and only near hilltops. Normally these are underlying rock materials under the covering loams on slopes of various gradients.

Deluvial sediments are the displaced covering loams. These crop out in ravines and lower parts of slopes, acting as the soil parent material. If combined with peat, deluvial deposits may form binomial parent materials. In particular, they underlay peat deposits on slopes adjacent to the floodplain.

Alluvial sediments of the Klyazma River are very diverse, often stratified, and have various grain size composition. Alluvial sediments are frequently mantled by peat.

Peat as a homogeneous soil parent material occurs sometimes in the floodplain and slopes adjacent to it. Much larger areas are occupied by binomial deposits: peat at various stages of decomposition with depths of 30–80 cm underlain by alluvium and/or deluvium.

Overall, each geomorphologic region has a specific set of soil parent material types that mostly do not overlap. In addition, considerable areas of various binomial deposits are present in all four geomorphologic regions; this reflects the lithologic inhomogeneity of the soil parent deposit.

During the morphological description of soil profiles in the field, it is difficult to determine whether the soil parent materials are homogeneous and/or inhomogeneous—in this case, they are binomial. A sharp difference in the natural characteristics of horizons within the 1-m layer is a criterion for the inhomogeneity identification [12]. An organic horizon (peat) underlain by alluvium is an example of a contrast binomial parent material. Another binomiality attribute is a distinctive difference in the grain size composition of the two adjacent soil horizons. A commonly accepted binomiality criterion is a difference of no less than one step in the content of physical clay particles (the sum of grain size fractions <0.01 mm) in the two horizons according to the classification proposed by N.A. Kachinskii. For example, a light loamy material in the upper horizons changes into a heavy loamy material in the B or BC horizon if the soil parent material is covering loams underlain by moraine deposits. Another example is sand loamy horizons underlain by sand deposits; in this case, it can be said that the covering loams are underlain by fluvioglacial sediments. It is also necessary to keep in mind the presence of stones >1 mm in diameter; this can be the reason for classifying soil parent material as binomial deposits even if the dispersiveness of fine earth (particles <1 mm) is the same. If the adjacent layers have a similar mineral composition, sediments with different dispersiveness are classified as noncontrasting binomial deposits.

METHODS

The field studies were performed during student summer field soil cartography training in 2012–2016. Soil profile locations were selected in accordance with instruction [11]. The soil pits were positioned using Garmin eTrex 10 GPS receivers. The GPS accuracy is ±5 m for open areas and ±7 m for forest areas.

The soil profiles were identified taxonomically using database [8]. Field journal descriptions were entered into the database in full by horizons, including the soil parent material type and grain size composition. To simplify the use of tabular data, a program interface based on Microsoft Access was used [6, 7].

The color of soil samples were analyzed with an X-Rite i1 Pro portable spectrophotometer (Switzerland). Spectrum analysis was performed on a holographic diffraction lattice with a photodiode matrix for 128 elements. The spectral range 380–730 nm; step was 10 nm; the measuring aperture has a diameter of 4.5 mm; USB interface; measurements in reflected light: measurement geometry is 45°/0°; A-type illuminant; the accuracy: 0.4 $\Delta E = 94$; the precision: 0.1 $\Delta E = 94$.

The soil samples were placed into plastic cups with the depth of 10 mm and diameter of 40 mm. The soil was pressed manually to ensure a homogenous, flat surface. Samples were air-dried for two days to ensure stabilization of the colour. Each soil cup was measured 11 times.

To produce a digital taxa map, five methods were used: K-Nearest Neighbors (KNN), Automated Neural Networks (SANN), Support Vector Machines (SVM), Match Method (MM) [10], and Sample-Based Method of Solim Solution 2013 (SOLIM) software [21].

The dependent variable was calculated as the belonging of a grid point (cell = 4 m) to a certain soil category. For the first three methods included in Statistica 10.0 [20], calculations were performed in two variants: (I) using only continuous independent variables (*X* and *Y* coordinates, height, slope, and plan and profile curvature) derived from the digital elevation model built earlier [10]—in all cases, default program options were used; and (II) in addition to the above predictors, the categorical geomorphologic index of the area was used [10]. For the MM and SOLIM methods, only variant II was used.

The dataset for digital map production was a table with 748 rows in accordance with the number of sampling points established during this period on the area of 338.9 ha. The data were divided into two parts: even- and odd-numbered soil profiles. To verify the predictive ability of the methods, we constructed a design map of the polygons from the calibration (training) sample, which included odd sampling points. The test sample consisted of even sampling points. Thus, both the training and the test samples contained data of all the years of the study in equal proportions.

The accuracy of the digital map was assessed using the overall accuracy index A_0 and *kappa* index [18].

When the method with the highest accuracy was chosen, the soil parent material map was produced based on all 748 sampling points (both even and odd).

SAGA 2.2.7 GIS [19] was used as a GIS platform. Data were pre- and postprocessed in the Access database management system (DBMS) [17] using automated software module [6].

RESULTS AND DISCUSSION

Accuracy assessment of digital maps of categories using various methods. The predictive power of each method (Table 1) was validated by analyzing the frequency of occurrence of the test points of field sampling in the polygons of the soil taxa calculated from the training (calibration) sampling points The prediction was considered correct, if the predicted and real values of the taxa were found at distances of no more than 7 m (in agreement with the average accuracy of georeferencing of test points (soil pits) in the field (±7 m).

Table 1. Accuracy of soil parent material maps produced using different methods

Method	Variant	A_0	*Kappa*
KNN	I	0.69	0.64
SANN	I	0.49	0.40
SVM	I	0.54	0.46
KNN	II	0.70	0.66
MM	II	0.74	0.70
SANN	II	0.63	0.57
SOLIM	II	0.68	0.63
SVM	II	0.64	0.57

The A_0 value in the table reflects the overall accuracy. The *kappa* index calculated in accordance with [18] shows that some of the apparent classification accuracy could be due to chance. This indicator is especially important when the number of classes (taxa) is small. In this case, the smaller the kappa, the higher the probability that the coincidence is purely accidental. As the number of classes increases or as the balance between classes becomes more even the probability of accurate prediction by chance falls.

With the calculation variant I, when only the continuous variables were used as predictors, both the map accuracy and *kappa* values were lower. When calculation variant II involving the geomorphologic index is used, the accuracy increases. The KNN and MM methods provide the closest and concurrently highest values. This is not surprising, since both methods use the same calculation algorithm: proximity of points to each other. MM was chosen for further calculations as the best in accuracy, available as an automated software module directly linked to SAGA GIS, which considerably simplifies the map production.

Use of color characteristics for soil parent material identification. In the process of soil survey, ~70% of soil horizons are distinguished by their color. Until recently, identification was performed only visually or using the Munsell Soil Color Chart at best. In this study, color identification was performed spectrophotometrically.

Table 2 shows the color characteristics of the main soil parent materials in the TESEC territory with the indication of soil horizons formed by these parent materials. It was found that their average lightness (L*), redness (a*), and yellowness (b*) values differ considerably. Dark organic horizons formed on peat have the lowest L*, a*, and b* values. Alluvial and deluvial sediments have similar characteristics but differ reliably in redness (a*) (Table 3): alluvium demonstrates lower values of this parameter. The transition from hydromorphic to automorphic positions can be traced by an increase in the average pit altitude over the sea level (Z).

Both the redness and yellowness of parent materials increase upwards from the floodplain (alluvium and peat) moving through slopes adjacent to the floodplain (deluvium) to covering loams and fluvioglacial and moraine deposits; this indicates an increasing content of trivalent iron in parent materials that largely determines the color of the horizons [11].

Table 3 shows the calculated significance of color differences between the soil parent materials on the basis of Student's t-criterion ($p = 0.95$). It was found that nine out of ten pairs of mineral (i.e., the most difficult to differentiate) soil parent materials can be distinguished by one to three color parameters. Mostly by redness (8), then by yellowness (6), and, least of all, by lightness (2). Moraine/fluvioglacial deposits are the only pair indistinguishable by color with $p = 0.95$. However, at $p = 0.90$, their difference in redness becomes statistically significant.

Therefore, spectrophotometric characterization of soil parent materials provides a reliable criterion for their differentiation. It is feasible to use this parameter to verify field identification data.

Analysis of the soil parent material distribution across the territory and geomorphological regions. Based on the findings, a digital large-scale soil parent material map has been compiled for the Chashnikovo TESEC (see Fig. 1 for black and white version; color version available in [5]).

The size of the study area is 338.9 ha. Binomial parent materials are most widespread: covering loams underlain by fluvioglacial sediments (17.2% of the total area) and covering loams underlain by moraine deposits (16.7%). Covering loams by itself occupy

Table 2. Color characteristics of soil parent materials (SE = standard error)

Soil parent material, horizon	N	Z, m	$L^* \pm SE_{L^*}$	$a^* \pm SE_{a^*}$	$b^* \pm SE_{b^*}$
Peat (T), A02, AT, T	37	186.7	29.1 ± 1.7	5.3 ± 0.3	8.1 ± 0.9
Alluvial sediments (A), AL, ALG	26	184.6	51.3 ± 1.7	5.6 ± 0.3	15.5 ± 0.7
Deluvial sediments (D), C	7	198.3	51.6 ± 6.2	7.0 ± 0.5	16.5 ± 2.0
Covering loams (Cl), B	15	208.1	53.5 ± 1.3	10.4 ± 0.4	22.2 ± 0.4
Fluvioglacial sediments (F), C	6	204.3	46.8 ± 0.9	11.1 ± 0.8	21.7 ± 1.0
Moraine sediments (M), C	4	212.0	49.6 ± 1.6	13.4 ± 0.9	23.4 ± 0.6

Table 3. Significance of color differences between soil parent materials using Student's *t*-criterion

Material I–Material II	a*	b*	L*
A–D	+	–	–
A–M	+	+	–
A–CL	+	+	–
A–F	+	+	+
D–M	+	+	–
D–CL	+	+	–
D–F	+	+	–
M–CL	+	–	–
M–F	±	–	–
P–F	–	–	+

Parent material symbols correspond to those in Table 2. "+" means significant differences; "–" is nonsignificant differences with $p = 0.95$. "±" is significant differences with $p = 0.90$.

7.9%, while deluvial sediments cover 6.6% of the total area. A considerable part of the area is occupied by alluvial sediments (14.5%), peat underlain by deluvial sediments (13.2%), peat underlain by alluvial sediments (12.9%), and alluvial sediments underlain by peat (8.4%).

The majority of the study area belongs to slope, terrace, and floodplain geomorphologic regions (Table 4). Slopes adjacent to the floodplain and ravines occupy smaller areas. A distinct pattern can be observed in the distribution of soil parent materials over the relief.

Soil parent materials of slopes and terraces are mostly represented by the covering loams underlain by fluvioglacial sediments, covering loams underlain by moraine deposits, and covering loams per se. In addition, small areas are covered by fluvioglacial sediments on elevated relief elements, deluvial sediments, or deluvial sediments overlaid by peat in the lower parts of the slopes.

Soil parent materials of ravines. There are two ravines in the study area: Durykinskii (in the northwest) and General'skii (in the southeast). They uncover sediments of the overlying slopes; therefore, in addition to the deluvial loam on the ravine walls and peat underlain by deluvium on the ravine bottoms, covering loams underlain by moraine or fluvioglacial sediments are also present.

Soil parent materials of slopes adjacent to the floodplain. The slopes adjacent to the floodplain are swamped despite drainage works. The widespread occurrence of peat underlain by deluvial sediments and peat per se is typical of this area. Part of this geomorphological region is neither bogged nor peated. In that part parent materials are represented by deluvial deposits.

Soil parent materials of the floodplain. Alluvial sediments of the Klyazma River are extremely diverse in texture, color, and other properties. In addition to alluvium, peat and peat–alluvium combinations are also present in the floodplain: alluvium underlain by peat and peat underlain by alluvium. In the soil profiles there are ironstone includings and marl horizons; clear stratification of the alluvial deposits can some-

Table 4. Distribution of soil parent materials by geomorphologic districts

Legend keys	Soil parent material	Slopes and terraces		Ravines		Slopes adjacent to the floodplain		Floodplain	
		A	B	A	B	A	B	A	B
1	Covering loams	23.4	16.5			3.5	7.3		
2	Covering loams underlain by moraine deposits	49.6	34.9	7.0	28.2				
3	Covering loams underlain by fluvioglacial sediments	57.8	40.7	0.4	1.6				
4	Fluvioglacial sediments	2.0	1.4						
5	Deluvial sediments	2.1	1.5	10.2	41.0	10.0	20.9		
6	Deluvial sediments underlain by peat			1.4	5.5				
7	Alluvial sediments							49.2	39.7
8	Alluvial sediments underlain by peat							28.6	23.1
9	Peat					2.9	6.0	2.4	2.0
10	Peat underlain by deluvial sediments	7.1	5.0	5.9	23.7	31.7	65.8		
11	Peat underlain by alluvial sediments							43.7	35.2
Total		142.0	100.0	24.9	100.0	48.1	100.0	123.9	100.0

A—area (ha), B—percent from the total geomorphologic region area

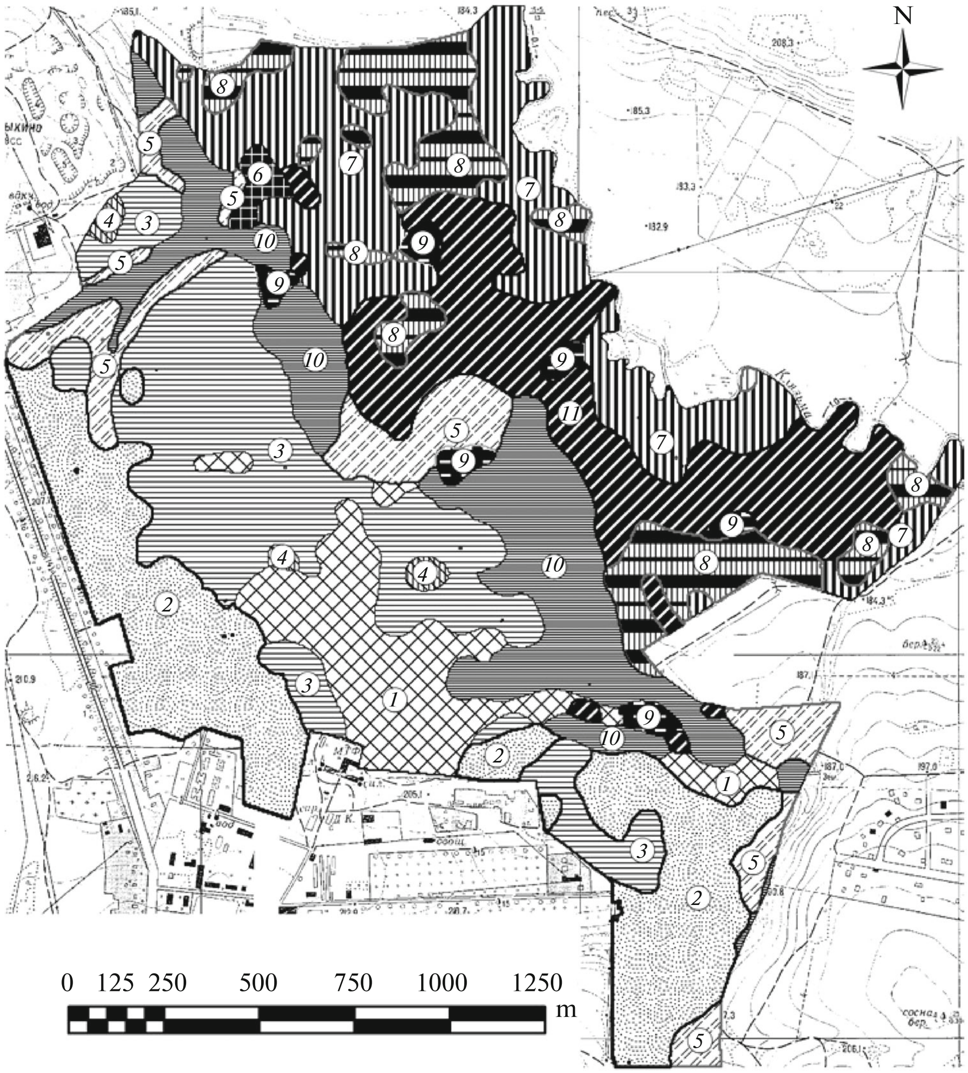

Fig 1. Digital soil parent material map of Chashnikovo TESEC: (*1*) covering loams , (*2*) covering loams underlain by moraine deposits, (*3*) covering loams underlain by fluvioglacial sediments, (*4*) fluvioglacial sediments, (*5*) deluvial sediments, (*6*) deluvial sediments underlain by peat, (*7*) alluvial sediments, (*8*) alluvial sediments underlain by peat, (*9*) peat, (*10*) peat underlain by deluvial sediments, (*11*) peat underlain by alluvial sediments.

times be observed. The bottom horizons are often gleyed.

CONCLUSIONS

(1) The application of digital processing methods (databases and automated taxa identification algorithms) to field data have made it possible to synchronize studies.

(2) The various methods used to compile the soil parent material map insignificantly affect the overall accuracy of the digital map if these include, in addition to continuous variables, a categorical predictor: the geomorphologic position of the sampling point.

(3) A statistically reliable criterion for soil parent material differentiation based on spectrophotometric properties in the CIE L*a*b* system has been proposed.

(4) A distinct pattern in the distribution of soil parent materials over the relief has been identified; it determines the soil diversity in the study area.

(5) Based on the extensive field data, the main soil parent material types have been identified for Chashnikovo TESEC and a large-scale digital map of them has been compiled.

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Translated by L. Emeliyanov