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NUMERICAL METHODS TO RECOGNIZE THE SOIL TYPES IN THE FOREST STEPPE

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The authors generalized and summarized original and literature data with the view of studying the gray and dark-gray soils in the Volga-Kama forest steppe. The methods of multidimensional statistics permitted to determine the position of these soils in the available soil classification system. A great number of soils described by different researchers within the framework of Russian soil classification system (1977) were formalized in conformity with that published in 2004. In the latest classification system of soils in Russia the reliable differences in the humus horizon of gray and dark-gray soils are shown in the content of humus, exchangeable bases, clay fraction, acidity and thickness as well as in the thickness of the leached layer (up to the C horizon) and the humus storage within the one meter of soil (t/ha). The methods of numerical classification allowed determining discriminated functions and classify more exactly the studied soils in the Volga-Kama forest steppe. Based upon statistic processing of the obtained data the limits for properties of the humus horizon are suggested to distinguish the gray and dark-gray soils. The visual imagination widely adopted now to recognize the types of gray and dark-gray soils should be added by limits of their varying properties. The obtained results presented in this paper may be useful to improve the idea on properties of gray forest soils. The suggested criteria to recognize the studied soils may be applicable for studying and systematizing these soils as well as for purposes of land use, elaboration of regional database and in projects of ecological territory optimization.

Keywords: gray soils, dark-gray soils, numerical classification, systematization.

When elaborating the classification schemes to recognize soils within their community in one or another region, it seems rather difficult to determine simple boundaries between taxonomic units. As a rule, the efforts of the author’s scheme are oriented to distinguish a central soil image to detect its taxonomic position. At the same time, the soil cover is a continuum, represented by a great diversity of soils, the latter being transitional to each other prove to be a matter of some difficulty to recognize them or to combine into groups according to the similar profile form, composition of the mineral mass, the humus content, etc.

In the present studies an attempt was made to generalize and summarize the ideas of many researchers in studying the soil cover within the Volga-Kama forest steppe and particularly the soils named as “gray forest soils” in the old soil classification. It became possible to carry out these studies in view of advancing electronic computers and programs corresponding to inquire of the science devoted to studying the soils and soil cover [16, 17, 18]. We created the registry data of 118 soil profile: Department of Soil Science Data of KFU, the data of literature sources [1, 5, 6, 10, 12, 22, 23]. These materials permitted to study the conditions for the development of the above soils occupied definite relief elements at the territory under consideration.

Table 1 shows the indices for the profile form in subtypes of gray forest soils. The major index is the texture differentiation that is reflected by differenced in the density and structure of soil horizons.

The granulometrical composition of soils closely associated with that inherent to soil-forming deposits that are conducive to the development of conditions for the organic matter and the most favorable soil structure [2, 4, 13]. Since the texture differentiation is reflected in uneven distribution of high-dispersed fractions along the soil profile, the A1 horizon was taken as a criterion for texture differentiation because just this horizon is found to be close to the atmosphere and subjected to transformation in the course of soil formation to a considerable extent.

The totality of gray forest soils according to the content of physical clay in A1 horizon is presented in Fig. 1. The content of physical clay is rather low (20–26%) in light-gray forest soils that have been developed on alluvial deposits in old river valleys of Volga, Kama and their great tributaries, where the fraction of medium and coarse sand makes up 47–56%. These soils differ from the other light-gray forest soils owing to the content of physical clay ($t_{ст}$ = 9.90 $t_{кр}$ = 2.88) and silt fraction (P = 0.016). The greatest content of physical clay (47–67%) is characteristic of dark-gray forest soils, the latter

Table 1. Indices for the profile form of virtual subtype images of gray forest soils

Horizon	*M*, см	Min	Max	*S*	*V*, %	*n*
Light-gray forest soil						
A1	20	12	26	4.00	19.9	22
A1A2	26	19	40	7.53	29.3	8
BA2	35*	25	46	5.90	6.0**	22
B1	60	45	75	10.19	16.9	21
B2	99	58	122	16.40	16.6	16
BC (BD)	135	110	156	15.79	11.7	11
Gray forest soil						
A1	18*	10	26	4.07	6.0**	39
A1A2	26	18	38	5.22	20.0	18
BA2	35*	20	48	6.09	8.0**	37
B1	55*	36	76	10.26	14.0**	36
B2	98	72	124	14.03	14.4	18
BC (BD)	145	113	164	16.22	11.2	12
Dark-Gray forest soil						
A	29	20	38	5.21	18.0	30
AB (BA2)	38*	31	57	7.24	13.0**	27
B1	62	47	77	7.98	12.9	25
B2	93	70	116	12.17	13.0	24
BC	112	80	145	24.23	21.7	13

* Median is used for non-parametric data.
** Interquarter scope.
Note: *M* – average arithmetical, S – standard deviation, *V* – variation coefficient, *n* – amount of observations.

being differed from light-gray ones have a great amount of high-dispersed fractions promoting the stabilization and accumulation of the organic matter [27]. The gray forest soils are developed on deposits in which the content of particles <0.01 mm accounts for 29–48%, thus gravitating towards the light-gray soils. Fig. 2 demonstrates a statistical position of soil subtypes with respect to the texture in the humus horizon. The data of statistical processing serve as evidence of texture heterogeneity in light-gray soils.

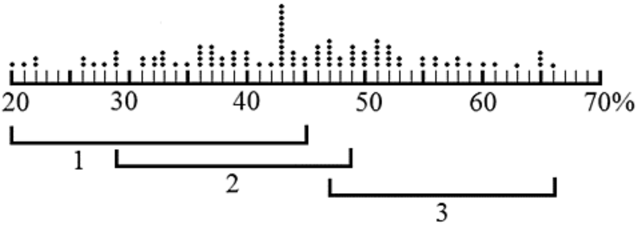

Fig. 1. Distribution of the content of physical clay in the humus horizon of gray forest soils (1 – light-gray, 2 – gray and 3 – dark-gray soils).

The soils of this taxonomic group are formed in natural regions, where the parent materials are presented by weathering products of permian and neogenic marl and old alluvial deposits transformed by aeolian processes. The dark-gray soils are combined into an individual group according to the content of physical clay and the silt content in it.

It is known that the parent material being initially homogenous is differentiated with time during the soil formation process but the composition of its lower part remains unchanged. The data presented in Fig. 2 II show a continuous row (from 32 to 73%) of physical clay in the C horizon of soil subtypes. It permits to assume a lithological homogeneity of the soil-forming material differentiated by natural processes and the soil formation in particular.

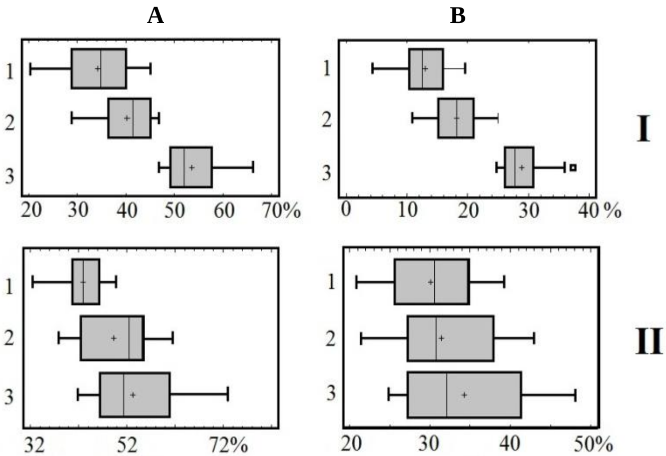

Fig. 2. Statistical position of gray forest soil types according to the content of physical clay (A) and the silt fraction (Б) in the humus horizon (I), in the parent material (II): 1 – light-gray, 2 – gray and 3 – dark-gray soils.

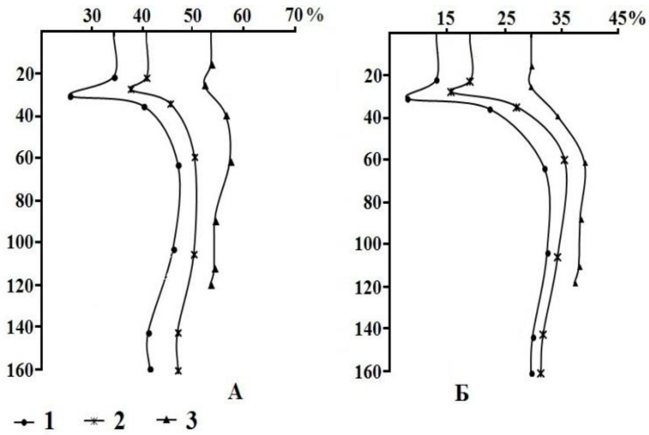

Fig. 3. The average content of physical clay (A), the clay (Б) in the profile: 1 – light-gray, 2 – gray and 3 – dark-gray forest soils.

Following the statement of several researchers the development of gray forest soils is accompanied by clay redistribution along the profile due to such processes as podzolization [8, 15, 20] or lessive [3, 11, 28] and the clay content is increased in middle and lower parts of the soil-forming material.

Fig. 3 shows the profile distribution of the physical clay content and its silt component. These data serve as evidence that the profile of all the soil subtypes is enriched not only with clay but also with physical clay to be maximum in the A1A2 horizon. The middle part of profile enriched with physical clay is specific for light-gray soils to a greater extent as compared to dark gray soils. This fact should be explained by a prolonged transformation of initial soil stratum caused by the soil formation process and exogenic changes in the parent material accompanied this process.

The major morphological and diagnostic feature of soil is differentiation of the soil profile, the quantitative characteristics of which is the differentiation coefficient (*S*). It is calculated as based upon the ratio between the content of coarse and fine sand fractions as well as the sum of sand particles and the content of coarse silt fractions in soil horizons [7, 14, 20, 24-26, 30,]. As a result it has been established that the light-gray soils (*S*=3.0) and gray forest soils (*S*=2.4) are characterized by highly differentiated profile, whereas the dark-gray soils are differentiated to a lesser extent (S=1.8).

The humus content in soil is an important feature of its fertility, closely correlated with physical properties, thus determining biological and numerous chemical processes in soil [13, 29]. Table 2 presents the data about the humus content and some physical-chemical properties in horizons of the gray forest soils. There is a correlation between the content of humus and calcium (r=0.8, P=0.000, n=70). The regression analysis was made to describe the linear dependence by the following equation: $y = 1.95 + 0.16\ x$, where x – the calcium content, meq/100, y – the humus content, %

The taxon identification by numerical methods Table 3 shows the results of claster analysis with k-averages and the interpretation amount equaled to 10. The following features were taken for this analysis: the humus content, the sum of absorbed bases, the content of the silt fraction and physical clay, soil pH in humus horizons. As seen from Table 3, the hypothesis of equal averages is rejected because the level of values for all the soil properties is less than 0.05.

The method of principal components was used for statistical verification of the total variation of the most informativecharacteristics. The first principal component displays correlation with the content of humus, physical clay, exchangeable bases and the dispersion of these features makes up 74% (Table 4). The second component correlates with the humus horizon thickness showing 16% of dispersion. The properties of the humus horizon in gray forest soils are presented in Fig. 4. It is evident that these soils are grouped into three subtypes including light-gray, dark-gray soils; the proper gray soils occupy the intermediate position and combine the properties of light-gray soils and peculiar features of dark-gray soils. The major part of gray forest soils is found to be close to subtypes of light-gray soils in terms of their morphology. As regards the dark-gray soils it should be noted that these soils have been developed on heavy parent materials, they are characterized by a higher content of humus (7.0–7.8%), exchangeable bases (27–35 meq/100) and cannot be referred to dark-gray soils due to the shallow A1 horizon (14–18 cm) and the presence of the A1A2 horizon. The close morphological configuration, profile differentiation, the absence of statistical differences in the profile distribution of fine-dispersed particles, humus and soil-pH permit

Table 2. Deviation diapason from average values of physical-chemical properties of the diagnostic horizons in the profile

Property	Light-gray forest, *n* =29	Gray forest, *n* = 24	Dark-gray forest, *n* = 34
Horizon A1			
Content of physical clay, %	20.3–45.3	28.8–46.9	47.1–66.2
Content of the clay fraction, %	4.3–19.5	10.8–25.3	24.5–37.4
pH H_2O	4.9–6.6	5.3–6.8	5.8–7.4
Content of humus,%	2.2–5.0	4.3–7.6	6.2–11.7
Base saturation, cmol(+)kg^{-1}	6.7–20.0	20.4–35.0	30.1–55.1
Horizon A1A2			
Content of physical clay, %	13.3–39.7	33.1–41.5	–
Content of the clay fraction, %	4.8–12.2	5.7–18.3	–
pH_{H2O}	5.2–5.5	5.3–5.9	–
Content of humus,%	0.39–2.07	1.23–3.80	–
Base saturation, cmol(+)kg^{-1}	2.2–16.0	10.7–18.7	–
Horizon B1			
Content of physical clay, %	33.6–58.7	41.4–61.2	47.2–76.8
Content of the clay fraction, %	22.5–45.8	20.0–45.0	30.3–49.3
pH H_2O	4.5–5.9	4.7–5.9	5.4–7.3
Content of humus,%	0.17–0.92	0.3–1.6	0.7–3.0
Base saturation, cmol(+)kg^{-1}	8.0–28.7	16.4–35.5	23.7–42.2
Horizon C			
Content of physical clay, %	32.5–49.8	37.8–61.6	41.9–73.0
Content of the clay fraction, %	20.9–39.2	21.3–45.4	24.9–48.1
pH H_2O	5.5–8.8	5.8–8.4	6.4–8.8
Content of humus,%	0.1–0.3	0.1–0.5	0.3–1.0
Base saturation, cmol(+)kg^{-1}	14.7–26.0	20.3–37.0	23.2–46.1

Table 3. Results of dispersion analysis

Feature	Sum of squares between classes	*df*	Total sum of squares in classes	*df*	*F*	*P*
Thickness	18.54	2	1475.95	77	48.38	0.0000
pH	2.01	2	21.29	77	3.63	0.0311
Humus	262.35	2	109.75	77	92.04	0.0000
Sum of exchange bases	7643.72	2	2391.35	77	123.06	0.0000
Fraction <0.001 mm	3669.14	2	1403.27	77	100.67	0.0000
Fraction <0.01 mm	6049.23	2	3102.42	77	75.07	0.0000

Table 4. Factorial coordinates of variables based upon correlations

Variable	ГК1	ГК2
Content of humus	–0.8938	–0.2591
Thickness of humus horizon	–0.6726	–0.7343
Content of physical clay	–0.8722	–0.0179
Sum of total bases	–0.9160	–0.2252

to combine the light-gray and gray forest soils into a type of gray soils/ The quantitative differences of some properties in the humus horizon are connected with peculiar features of parent materials that determine the intensity of the soil formation process.

Having substantiated the data of the profile morphology in soil subtypes and statistical processing of data about the lower part of their horizons, it was managed to create virtual images (standards) of gray and dark-gray soils within the Volga-Kama forest steppe (Fig. 5). They proved to be different in the content of humus ($P = 9.47 \times 10^{-12}$), exchangeable bases ($P = 6.65 \times 10^{-10}$) the silt fraction ($p = 0.000$), the clay fraction ($P = 2.03 \times 10^{-9}$) in the upper 0-20 cm layer. The differences were also observed in the acidity ($t_{ст} = 3.91$, $t_{кр} = 2.63$), in the

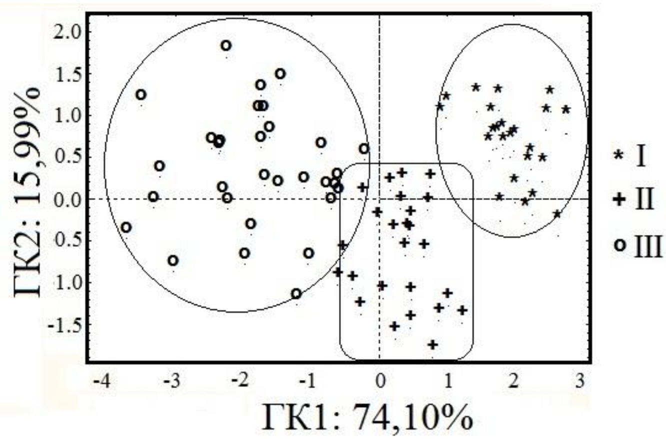

Fig. 4. Visualization of the humus horizon properties in subtypes of gray forest soils at the factorial plane of the principal component 1 – the content of clay fractions, exchange bases, humus; the principal component 2 – the thickness of the humus horizon I – light-gray, II – gray and, III – dark-gray forest soils.

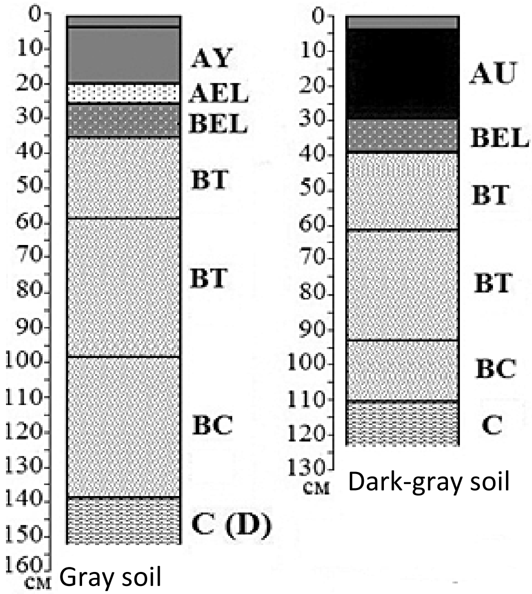

Fig. 5. Central images of gray and dark-gray soil types.

thickness of the humus horizon (P = 0.000) as well as in the thickness of the leached stratum up to the C horizon (P = 0.0035) and the humus storage in the 0–100 cm layer ($t_{ст}$ = 4/89, t_{kp} = 2.98).

The discrimination method was used to identify the gray forest soils in the soil classification of 1977 and the gray and dark-gray soils in the classification of 2004. There are two discriminated functions in the classification of 1977, the first of them shows 87% of dispersion being correlated with the humus content (P = 0.004), exchangeable bases (P = 0.000) and physical clay (P = 0.006), the second function reveals 13% of dispersion and correlates with the thickness of the humus horizon (P = 0.000). The classification matrix evidences that the light-gray and gray forest soils have been correctly classified (100%), the dark-gray soils – 90%. The classification functions are the following:

$$S_1 = -0.04x_1 + 0.64x_2 + 2.26x_3 + 1.00x_4 - 24.43,$$
$$S_2 = 0.30x_1 + 0.75x_2 + 3.60x_3 + 0.75x_4 - 37.80,$$
$$S_3 = 0.35x_1 + 0.90x_2 + 4.87x_3 + 1.42x_4 - 69.81,$$

where S_1 – the totality of light-gray forest soils, S_2 – the totality of gray forest soils, S_3 – the totality of dark-gray forest soils, x_1 – the sum of exchange bases, x_2 – the content of physical clay, x_3 – the humus content, x_4 – the thickness of the humus horizon.

The results of the discriminated function in soil classification of 2004 showed that the reliable variables seemed decreased to discriminate the types of gray and dark-gray soils. Since two soil types are compared, there is only one discriminated function correlating with the thickness of the humus horizon (P = 0.000), the humus content (P = 0.000) and physical clay (P = 0.018), thus determining 100% of dispersion. The decrease in reliable variables is probably connected with the fact that the discrimination analysis takes into account not only the value and variation of every soil property but also their interaction between each other.

The classification matrix showed that the gray soils were correctly classified (100%), the dark-gray soils – 97%. The classification functions can be presented in the following way:

$$S_1 = 1.02x_1 + 1.69x_2 + 0.49x_3 – 22.51,$$
$$S_2 = 1.68x_1 + 3.13x_2 + 0.63x_3 – 52.87,$$

where S_1 – the totality of gray soils, S_2 – the totality of dark-gray soils, x_1 – thickness of the humus horizon, x_2 – the humus content, x_3 – the content of physical clay.

In search of real representatives of central virtual soil images for their taxonomic position 15 soil sections have been studied under the broad-leaved forests in the Republic of Tatarstan.

The central image of the gray soil (section 12) is located at the territory of Yantykovski forest massive ($35^0$36.938’N, $49^0$37.481’E, elevated by 182 m); this soil was developed under linden with admixture of oak and birch (Fig. 6A). The undergrowth is represented by maple and linden. The terrestrial cover consists of *Aegopodium podagrariaL, Pteridium aquilinumL, Polygonatum multiflorumL, Asperula graveolensL, StellarianemorumL, Lamium maculatumL, Geranium sylvaticumL*. The soil is gray in color, typical, saturated, highly leached, heavy loamy on eluvium of Permian deposits; it is close to a central virtual image according to the profile form. The content of humus in the humus horizon is 5.0%, the content of absorbed bases – 18.5 meq/100g. The soil pH is medium-acid. At a depth of 40–60 cm there is a horizon, where the substances leached from overlying layers are accumulated in the kind of fine-dispersed particles. Cutans close to the carbonate parent material become darker in color. Local carbonate effervescence is observed at a depth of 107 cm. Changes in the humus content and base saturation along the profile are close to the diapason of average values for the standard of gray forest soils (Fig. 7A).

The central image of dark-gray soil was taken in section 16 located at the territory of Bilyarski forestry farm in the Republic of Tatarstan (54°54.584'N, 50°33.985'E, elevated by 175 m). The forest vegetation is presented by linden and maple with the undergrowth of maple, linden and ask. The terrestrial cover consists of *Aegopodium podagraria L, Convallariamajalis L, Polygonatum multiflorum L., Asarum europaeum L., Glechoma hederacea L., Stellarianemorum L., Stachys sylvatica L., Aconitum septentrionale L.*

The soil is typical, saturated, moderately leached, heavy loamy on carbonate clay. The clayey-coarse-silt humus horizon has the crumby-granular structure and a higher content of humus (8.5% in the 15 cm topsoil). The absorbed base saturation makes up 37.6 meq/100 g.

A B

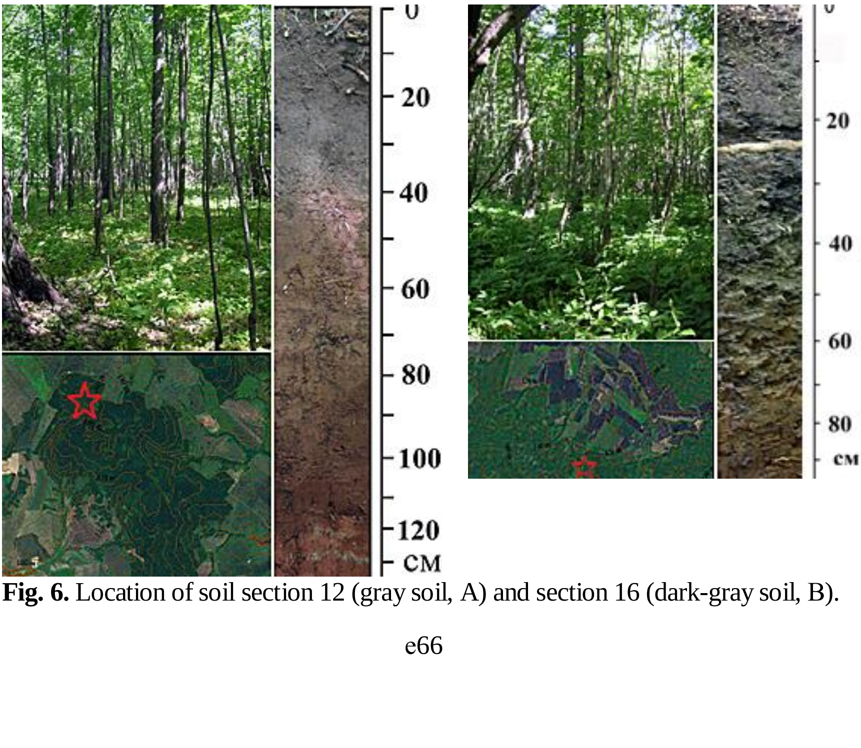

Fig. 6. Location of soil section 12 (gray soil, A) and section 16 (dark-gray soil, B).

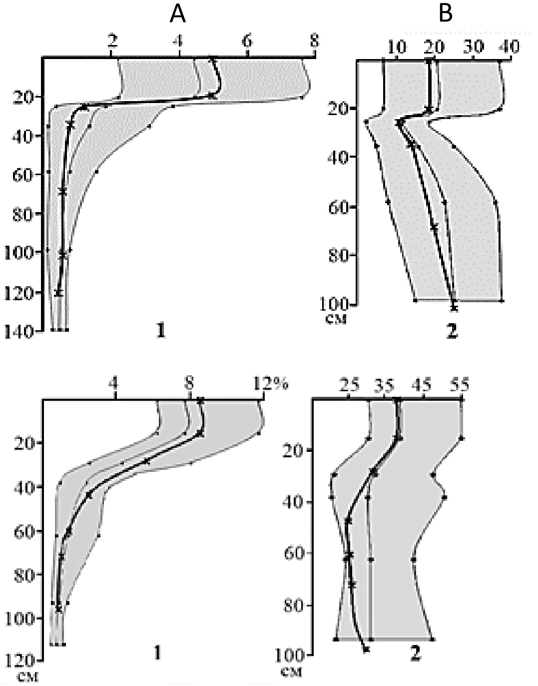

Fig. 7. The basic properties of the real representatives of the gray (A) and dark gray soil (B) in the range of variation of the model: 1 – humus content, %; 2 – the amount of absorbed bases, mmol (eq)/100 g.

pH of the topsoil is neutral, at a depth of 40-80 cm it is medium and strongly acid (5.6–5.3). The horizon with the maximal content of the silt fraction is found to be at a depth of 50–60 cm. Cutans close to the parent material become darker in color. Local carbonate effervescence takes place with the depth of 72 cm. The changes in the humus content along the profile are close to average values (Fig. 7Б). The base saturation and the acidity in the humus horizon are also similar to average values of the dark-gray forest soil. However, in the subeluvial profile their values are approximated to the limit that is probably associated with the initial heterogeneity of the soil-forming stratum. The value of acidity is close to that in the gray soil (pit 12) being conditioned by the presence of exchange hydrogen in the soil absorbing complex.

CONCLUSIONS

The materials presented in this paper with the view of substantiating the ideas of gray forest soils within the forest steppe zone and their recognition at a type level by using digital methods permit to draw the following conclusions.

1. In zonal soil system of the forest steppe the profile form, chemical and physico-chemical properties of forest soils confined to relief elements that are additionally moistened due to redistribution of atmospheric precipitation by surface and subsoil runoff and/or decreasing the evaporation are highly dependent on the granulometrical composition of soil-forming deposits.

2. This dependence is clearly manifested in the surface (humus) horizon including the thickness of this horizon, the humus content, pH and its distance from the carbonate horizon.

3. The totality of forest soils within the Volga-Vyatka forest steppe recognized at three subtypes in the old soil classification is classified now at the type level of gray and drk-gray soils.

4. For practical utilization the following limits are proposed to recognize the gray and dark-gray forest soils according to the properties of the humus horizon at the territory of the Volga-Kama forest steppe

Properties	Gray soils	Dark-gray soils
Content of physical clay, %	20–46	47–66
Content of silt fraction, %	4–24	25–37
Thickness of the humus horizon cm	10–23	24–38
Content of humus, %	2–7	7–12
Sum of exchange bases, meq/100g	7–34	35–55
Soil pH (H_2O)	5–6	6–7

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