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Soil cover patterns in the forest-steppe and steppe zones of the East European Plain

Abstract: The soil cover of the forest-steppe and steppe zones of the East European Plain is characterized by diverse soil combinations revealed during large-scale and detailed soil mapping against the background of a traditional zonal sequence of dominant automorphic soils alternating from the north to the south and clearly displayed on small-scale soil maps. The composition, configuration and functioning of particular soil cover patterns are determined by the soil forming factors acting within a given area. The elementary soil areas (detailed scale) and elementary soil cover patterns maps (large scale) of the Central Russian, Kalach, and Volga Uplands are created by both traditional and digital soil mapping methods. Low-contrasting soil combinations with the background Haplic Chernozems (Loamic or Clayic, Pachic) alternating with zooturbated Haplic Chernozems (Loamic or Clayic, Pachic) on convex elements of the microtopography and Luvic Chernozems (Loamic or Clayic, Pachic) on concave elements of the microtopography prevails under conditions of thick clay loamy parent materials and free drainage. Under conditions of shallow embedding by low-permeable clayey sediments, the soil cover includes Chernozems or Chernic Phaeozems with stagnic features in some part of the soil profile or even Mollic Stagnosols. The presence of shrink-swell clays of different ages leads to the formation of Bathyvertic Chernozems, Vertic Chernozems, Vertic Chernic Phaeozems and/or Pellic Vertisols. The presence of soluble salts in the parent material leads to the development of solonetzic soil complexes consisting of Protosodic or Sodic Chernozems and different types of Solonetzes.

Keywords: Chernozems, Phaeozems, soil mapping, pedodiversity, WRB

INTRODUCTION

The climatic conditions of the forest-steppe zone with favorable water-air and temperature regimes for plant residue humification contribute to the formation of Chernozems, the most fertile of all natural zonal soils on Earth. In Russia, Chernozems occupy interfluves and slopes in the forest-steppe and steppe vegetation zones; their area is estimated at 93 246 000 ha, or about 7% of the total area of Russia (Shishov et al. 2001). In the East European Plain and West Siberian Lowland, forest-steppes and steppes extend in the zonal direction as continuous zones; further to the east, they occur in isolated intermontane depressions (Fig. 1). A significant part of the area is used for rainfed farming.

The soil cover of the chernozemic zone as reflected on small scale maps may create an erroneous impression of its simplicity, though the legend of the *Soil Map of the Russian Federation* on a scale of 1:2.5 M includes separate units of dominant soils and combinations of several soils (Fridland 1988). Chernozems are dominant soils in the forest-steppe and steppe zones. Many publications are devoted to their genesis, geography, properties, functioning regimes and utilization (Dokuchaev 1948; Prasolov 1939; Fridland 1972, 1974; Bolshakov 1961; Sokolov and Shkonde 1963; Afanasyeva 1966; Kokovina 1974; Agrophysical characteristics of the soils of the steppe ... 1977). However, chernozems often occur together with a wide range of other soils. Differentiation of the soil cover patterns in the chernozemic zone is controlled by the elements of the meso and microtopography, the character of parent materials, and the depth of the groundwater table. The theory of soil cover pattern was first proposed by V.M. Fridland (1919–1983). Fridland's concept allows us to depict heterogeneity of the soil cover at various hierarchical levels of its organization. Depending on the scale, separate elementary soil areas and elementary soil cover patterns consisting of dominant and accompanying soils can be shown. The key position in the theory of the soil cover pattern is the analysis of the relationships between the soil cover components, their genesis and evolution, their spatial arrangement and their mapping.

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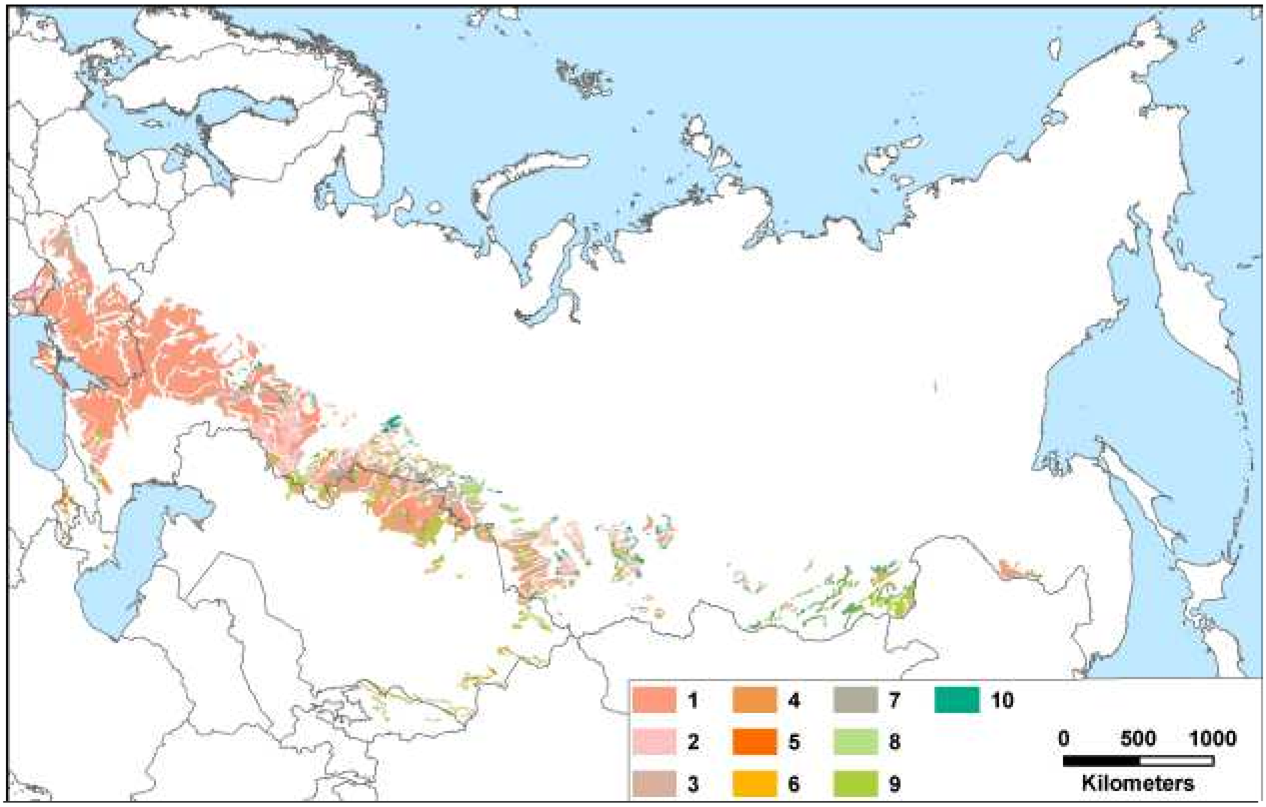

FIGURE 1. Distribution and use of Chernozems in Russia and neighboring countries (within the borders of the former USSR): (1) cropland >80%; (2) cropland >50% and natural rangeland; (3) cropland >50% and forest; (4) irrigated cropland; (5) cropland in mountainous regions; (6) cropland in valleys; (7) mown meadow and rangeland with cropland (<30%) and forest; (8) mown meadow and rangeland with cropland (<20%), forests, and bogs; (9) steppe rangeland with cropland (<20%); and (10) forest and woodland with rangeland and cropland (<20%)

In this paper, we characterize the soil cover in the forest-steppe and steppe zones of the European part of Russia on detailed and large scales. The specific objectives of our investigation are to determine the leading factors controlling spatial soil variability on the basis of long-term field research of separate soils and soil cover patterns in the Central Russian, Kalach and Volga Uplands conducted mainly by researchers from the Dokuchaev Soil Science Institute. The methodological framework of our study is based on the theory of the soil cover pattern (Fridland 1972), the evolutionary-genetic model of the spatial organization of the soil cover (Goryachkin 2010), and the functional component of soil cover patterns (Kozlovsky 2003). Maps of the elementary soil areas (detailed scale) and elementary soil cover patterns (large scale) are created by both traditional and digital soil mapping methods.

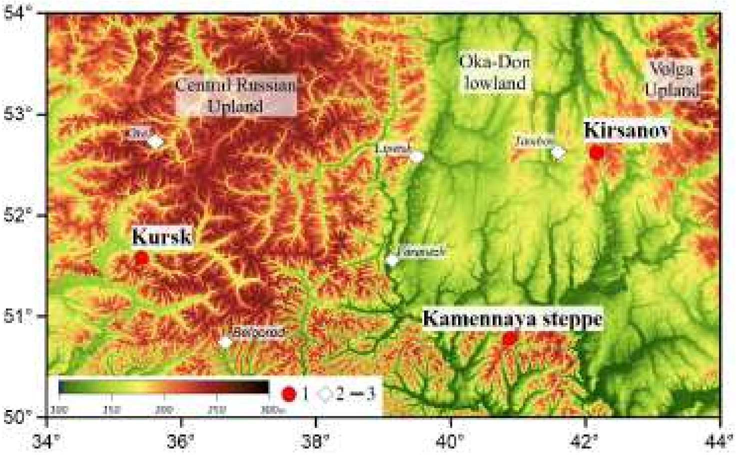

FIGURE 2. Topographic map of the Central Chernozemic region of Russia and location of key polygons: (1) key polygons, (2) big cities, and (3) boundaries of large geomorphic regions.

MATERIALS AND METHODS

Key polygons are located on the Central Russian Upland (Kursk polygon), the Volga Upland (Kirsanov polygon) and the Kalach Upland (Kamennaya Steppe polygon) (Fig. 2). A number of plots confined to different elements of mesotopography were investigated on each of these polygons. The climate of the studied regions is moderately continental and humid, with mean annual precipitation of 450 to 600 mm (for the period 1975–2000) aridity index (the precipitation-to-potential evaporation ratio) close to 1 and the accumulated sum of active daily temperatures about 2400–2500 degree-days. The main differences between the plots are in the parent materials (controlling the chemical composition and physical properties of the soils) and specific features of the topography.

Kursk polygon

The Kursk polygon (Fig. 3a) is located in the Alekhin Central Chernozemic Nature Reserve (Kursk region, 36°10'E, 51°36'N). Parent materials are loesslike loams with a thickness of up to 8 meters. The upper stratum on the interfluve plains is clay loam of the Riss and Würm glaciations; these sediments are underlain by loams of the Gunz and Mindel glaciation overlying the Cretaceous chalkstone. Soils of the polygon were formed under free drainage conditions; the groundwater table depth is more than 6 m. The loesslike loams largely contribute to the active development of ravines on the slopes and the network of shallow hollows on flat interfluves. The burrowing activity of marmots *(Marmota bobak)* and mole rats *(Spalax*

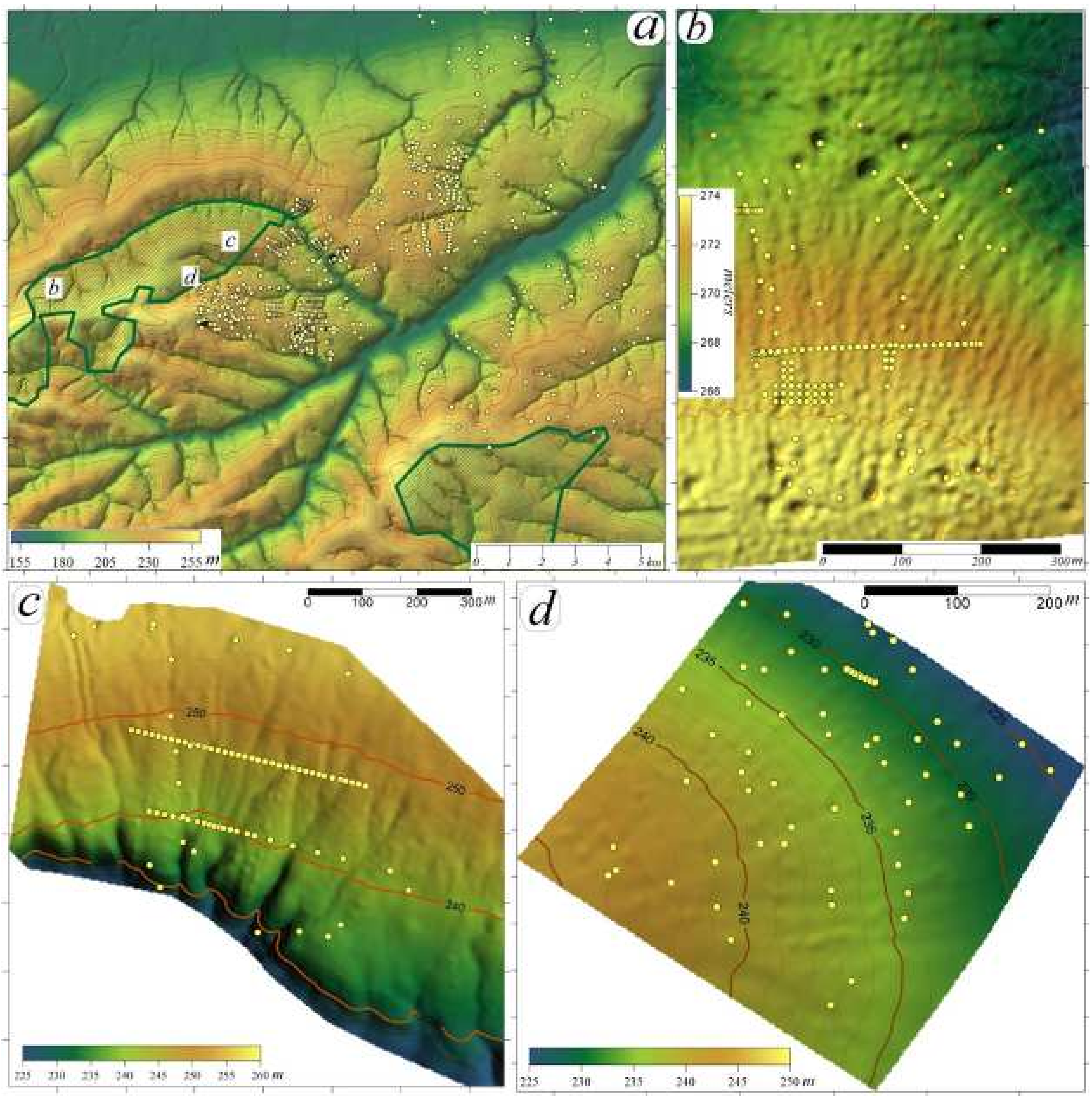

FIGURE 3. Digital elevation models of key plots of the Kursk polygon (a), Kursk-1(b), Kursk-2(c), Kursk-3 (d)

microphthalmus) contributes to the formation of zoogenic micro and nanotopography: 5–7 m in diameter and up to 0.5 m in height (Yeremenko and Panin 2010). Detailed mapping of the key plots (Fig. 3) was performed to characterize the general morphology of uplands and slopes (Mikhno et al. 1983). Absolute altitudes of the interfluve are 265– 275 m and 225–260 m for the slopes.

The microtopography of plot Kursk-1 (Fig. 3b) on a gentle (up to 1.5°) slope of northern aspect is complicated by a network of erosional hollows and by small closed suffosion depressions within plain surfaces on the upper and lower parts of the slope. Plot Kursk-2 is allocated to a steeper (>3°) slope of southern aspect (Fig. 3c) dissected by ravines. Plot Kursk-3 characterizes a gentler slope of northeastern aspect complicated by a network of shallow hollows. The nanotopography of these plots is complicated by marmot's burrows and mole rat holes. Overall, 157 soil profiles were described. The topography was studied in detail by GNSS surveys. Two Stonex S9III+ GNSS receiver were used. A digital elevation model with 2.5-m resolution was developed using an ordinary kriging method (Oliver and Webster 2015). The maps of elementary soil areas and elementary soil cover patterns were obtained by digital soil mapping involving linear discriminant analysis (Webster and Burrough 1974; Bell et al. 1994; Kozlov et al. 2018).

Kirsanov polygon

The Kirsanov polygon is found on a slightly undulating poorly dissected interfluve between the Tsna and Vorona rivers (42°25'E, 52°50'N, Tambov region) with absolute altitudes of 200–220 m. The parent materials have low hydraulic conductivity: loesslike clay loams underlain by clay loamy boulder moraine of the Gunz glaciation or by lacustrine clays at the depths of less than 3 m (Dudnik et al. 2013).

Field studies were carried out on three types of terrain (Fig. 4): (a) nondrained interfluve plain; (b) slightly drained interfluve plain dissected by the upper reaches of ravines and (c) surface-drained slightly inclined plain dissected by a network of hollows, ravines and small-river valleys (Milkov 1976). The mesotopography between the interfluve areas is complicated by microlows of the thermokarst and suffosion origins that accumulate runoff flows

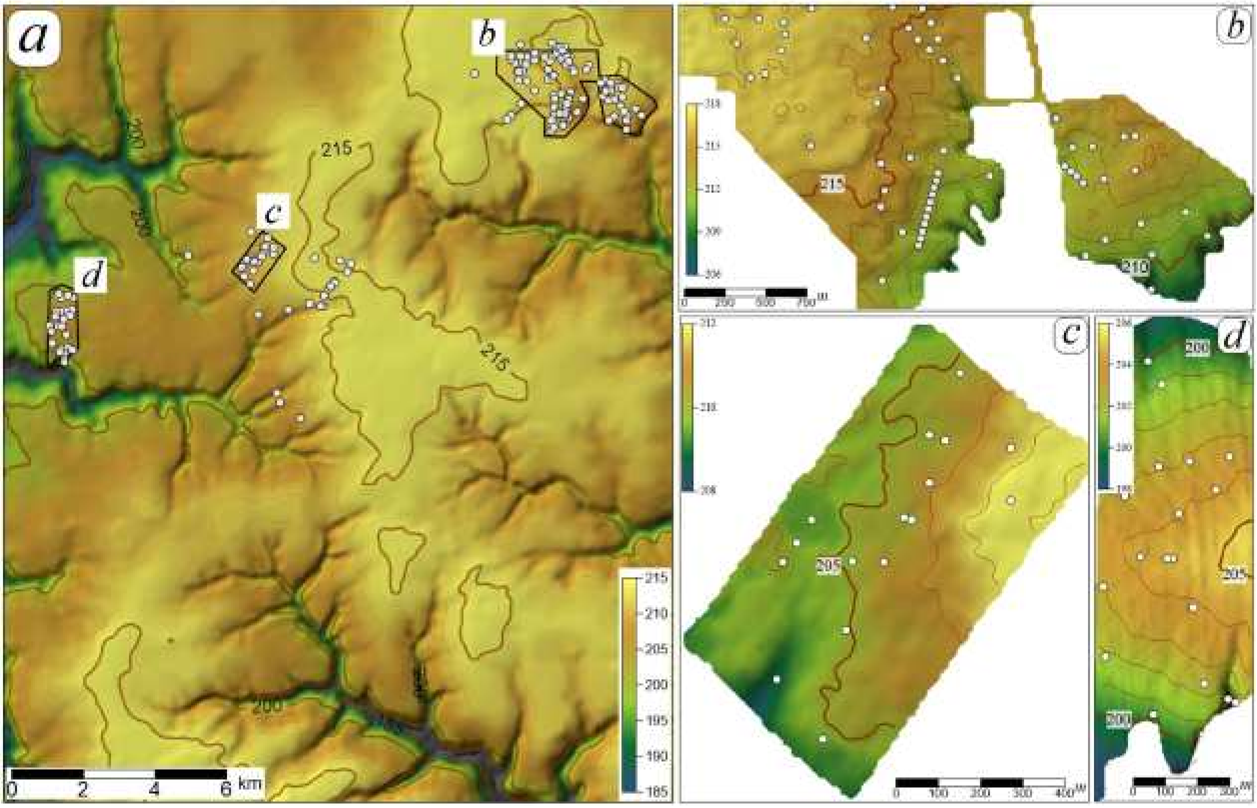

FIGURE 4. Digital elevation models of key plots of the Kirsanov polygon (a); Kirsanov-1 (b); Kirsanov-2 (c); and Kirsanov-3(d)

and provide for the preferential downward water flow throughout the soil and vadose zone thus regulating the groundwater level and water reserves in the soils. The maximum density of these microlows is in the area of the nondrained terrain, where water stagnation after snow melting can persist up to 2–3 months during wet years (Rode 2008; Levchenko et al. 2019). The depth of bicarbonate-calcium waters varies within 1.5–3 m on nondrained interfluve, 4–6 m on slightly drained interfluve, and is more than 6 m on surface-drained interfluve. In total, 27 soil pits and 114 boreholes were examined. Maps of elementary soil areas and elementary soil cover patterns were created using linear discriminant analysis. The digital elevation model (Fig. 4) with 20-m resolution was created based on the detailed topographic survey.

Kamennaya Steppe polygon

Kamennaya Steppe is located on the northern spurs of the Kalach Upland in the central part of the interfluve between the Bityug and Khoper rivers (left tributaries of the Don River) in the Talovaya district of Voronezh region. The predominant landforms are a broad flat watershed plain between the Chigla River and the Talovaya balka (flat-bottomed ravine) complicated by shallow closed depressions and upper reaches of hollows and ravines; its relatively steep eastern slope towards the Talovaya balka, and a gentler and longer western slope towards the Chigla River are dissected by numerous ravines passing into deeply incised balkas. Surface deposits are thick (8–10 m) Quaternary loesslike clays and clay loams subdivided into three layers differing in their ages. These sediments are underlain by the moraine of the Gunz glaciation with a thickness of up to 10 m (Basov and Grishchenko 1963). In some places on the slopes of the Talovaya balka, the moraine outcrops to the surface and serves as parent material.

The climate is relatively dry and continental. Previously, there were frequent droughts and dry hot winds (Vinokurova 1967). At present, they are weakened due to the forest plantations and a set of measures to regulate the water regime of the territory. The aridity index is 0.56–1.23 (mean – 0.86). For mapping soil cover patterns, several mutually complementary approaches have been used. The first of them is the systematization of various materials on the geological and hydrogeological structure, topography, climate, vegetation, soil cover, and economic activity obtained by specialists over more than a century (since the first studies in 1892).

The second approach is a multi-scale mapping of the soil cover based on a combination of direct field surveys on key areas and remote sensing methods. During the field survey, 1157 sampling points were described. In addition, information about the location and morphological descriptions of 150 soil profiles made during the survey in the 1940s was used (Pershina et al. 1947). The author's names of the soils found in the legend to the mentioned map and also in the typewritten report were interpreted in terms of the WRB-2014 on the basis of available morphological descriptions. A direct mapping of soil areas with seasonal manifestation of surface waterlogging was conducted in 2006–2008.

The third approach is the creation of GIS project with a digital elevation model, remote sensing materials, scheme of forest plantations, results of the field soil survey and the map of soil cover patterns. The map of soil cover patterns was developed using the methodology of digital soil mapping (Kozlov et al. 2008).

RESULTS AND DISCUSSION

Kursk polygon

According to the WRB-2014, the soils of this polygon belong to two reference soil groups: Chernozems and Phaeozems. A common feature of the soils is a very dark, granular, thick (60–80 cm, Pachic qualifier) and humus-rich (>5% C_{org}, Hyperhumic) chernic horizon in the upper part of the profile. In Haplic Chernozems, under the chernic and mollic horizons, a carbonate-accumulative horizon is found; it contains secondary carbonates (protocalcic properties) in the form of fibers of 0.5–2 mm in thickness and tubules along the walls of cylindrical pores with a diameter of 1–1.5 mm (pseudomycelium). Protocalcic properties can be diagnosed in the humus horizon in the case of soils subjected to zooturbation. In some soils, an argic horizon is located between the humus and the carbonate-accumulative horizons. It does not contain carbonates, and all sides of peds are covered with thin single-layer coatings (Luvic qualifier). When the argic horizon is thicker than 50 cm, the soils are identified as Chernic Phaeozems. In the illuvial horizons of some soils, there may be iron-manganic nodules attesting to periodic moisture stagnation (Stagnic qualifier) and silt and sand particles on ped faces (Greyzemic qualifier).

The soil cover of the investigated area is represented by Haplic Chernozems (Loamic, Hyperhumic, Pachic), Luvic Chernozems (Loamic, Hyperhumic, Pachic), and Luvic Chernic Phaeozems (Loamic, Hyperhumic, Pachic) on the flat interfluve; zooturbated Haplic Chernozems (Loamic, Hyperhumic, Pachic) on convex elements of microtopography, including relic marmot's burrows, and on steep slopes of ravines; and Luvic Stagnic Chernic Phaeozems (Loamic, Hyperhumic, Pachic) and Luvic Greyzemic Stagnic Chernic Phaeozems (Loamic, Hyperhumic, Pachic) in the bottoms of hollows and closed depressions.

Soil cover patterns on the interfluve plain (Kursk-1 plot, Fig. 5b) are represented by low-contrasting soil combinations of Haplic Chernozems with Luvic Stagnic Chernic Phaeozems and Luvic Greyzemic Stagnic Chernic Phaeozems, which usually occur as rounded or amoeboid areas among the dendritic areas of Luvic Chernic Phaeozems and Luvic Stagnic Chernic Phaeozems. On the northern slope (Kursk-2 plot, Fig. 5c), there are no rounded areas of Luvic Stagnic Chernic Phaeozems, and the spatial pattern, in general, resembles that of the upland plot. On the western slope (Kursk-3 plot, Fig. 5d), the areas of Luvic Chernic Phaeozems and Luvic Stagnic Chernic Phaeozems acquire a more manifested dendritic pattern in comparison with the upland and northern

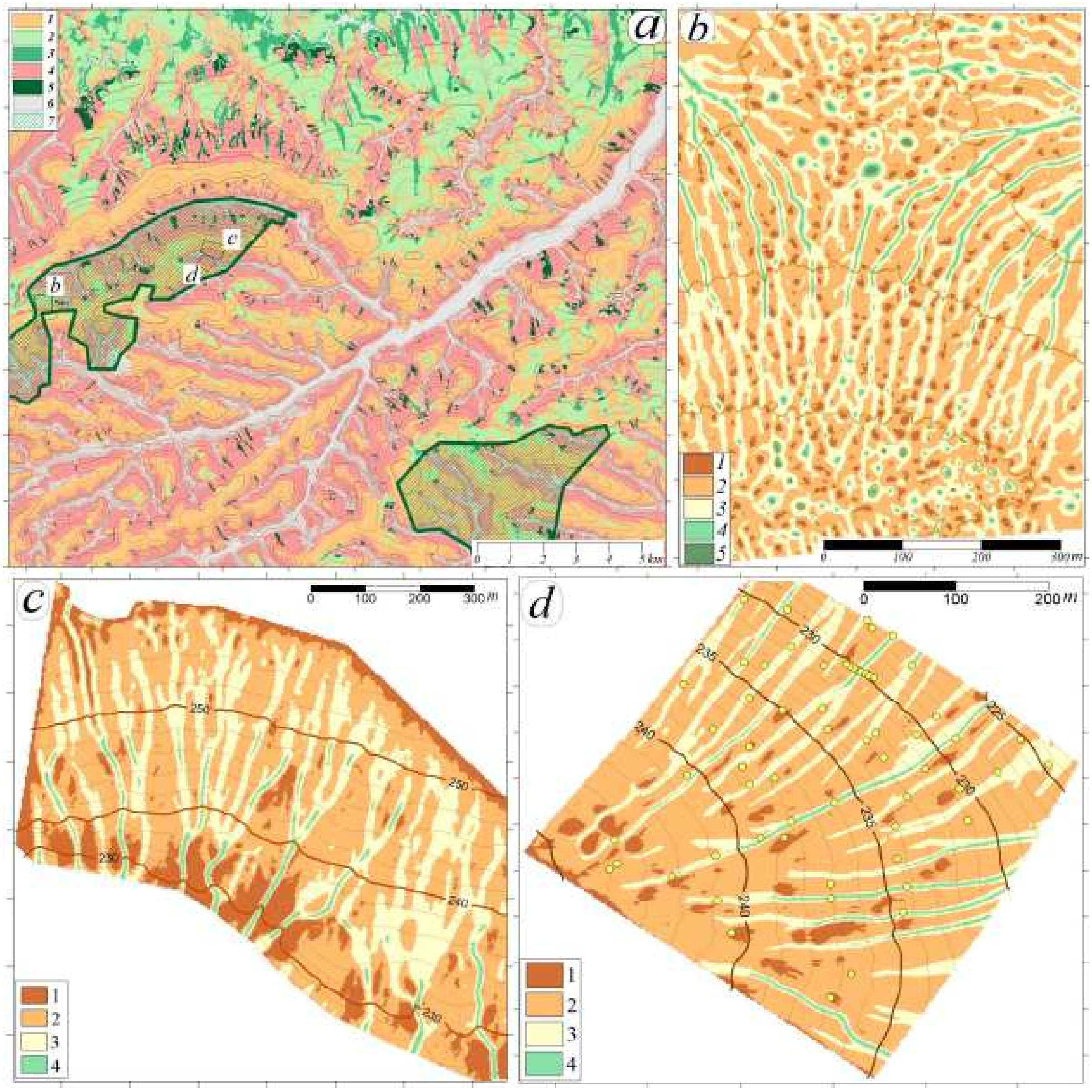

FIGURE 5. Soil cover patterns in the forest-steppe of the Central Russian Upland (Kursk polygon). Abbreviations of soil units are given according to IUSS Working Group WRB (2015). Components of soil combinations are listed in the decreasing order of their portion in the composition of soil combinations: (a) general view of the polygon and location of key plots; 1-CH-ha-lo.jh.ph, CH-lv-lo.jh.ph, PH-ch.lv-lo.jh.ph, PH-ch.st.lv-lo.jh.ph (Automorphic); 2- CH-ha-lo.jh.ph, CH-lv-lo.jh.ph, PH-ch.lv-lo.jh.ph, PH-ch.st.lv-lo.jh.ph, PH-ch.st.lv.gz-lo.jh.ph (Automorphic-semi-hydromorphic), 3-PH-ch.st.lv-lo.jh.ph, CH-ha-lo.jh.ph, CH-lv-lo.jh.ph, PH-ch.lv-lo.jh.ph (Semi-hydromorphic), 4- CH-ha-lo.jh, CH-lv-ce.jh, (Erosional), 5- PH-ch.st.lv-lo.jh, PH-ch.lv-ce.jh.,CH-ha-lo.jh, CH-lv-lo.jh (Semi-hydromorphic-erosional), 6-Not representative area; 7-Reserve (b) Kursk-1, (c) plot Kursk-2, and (d) Kursk-3. Soils: 1-zooturbated CH-ha-lo. jh.ph 2-CH-ha-lo.jh.ph, 3-CH-lv-lo.jh.ph and PH-ch.lv-lo.jh.ph, 4-PH-ch.st.lv-lo.jh.ph, 5-PH-ch.st.lv.gz-lo.jh.ph

parts of the slope. On the lower parts of the slope, large areas of zooturbated Chernozems are formed on extremely convex surfaces between hollows.

The analysis of the of soil cover pattern maps and the digital elevation model attests to a clear relationship between soil areas and the topography specifying changes in the runoff distribution. With an increase in runoff, the depth of soil moistening increases, which is accompanied by the change in the distribution of soil carbonates (Lozbenev et al. 2019).

The soils on convex elements of the microtopography contain dispersed calcium carbonates from the surface or within a layer at 10–30 cm owing to the activity of burrowers (marmots, mole rats, and gophers) that transport material from the lower calcareous horizon to the surface or into the dark humus horizon while digging their holes and sleeping chambers. The long-term mixing of the introduced material with the material of the humus horizon takes place. Thus, the upper part of the profile – dark-humus chernic and deeper mollic horizons – contains dispersed carbonates and characterized by an increased thickness due to the transfer of humified material down into the profile. In the middle part of the profile, a strongly zooturbated carbonate-accumulative with calcitic pseudomycelium is present. The BC and C horizons often include sleeping chambers and many former tunnels filled with material displaced from other horizons. Zooturbated Haplic Chernozems (Loamic, Pachic) are formed on convex elements of the microtopography with minimal soil moistening from the surface and protection of the animal burrows from flooding.

Relatively flat elements of the microtopography are occupied by dominant soils – Haplic Chernozems (Loamic, Pachic). Precipitation moisture provides for the normal soil moistening and leaching of calcium carbonates; the upper boundary of dispersed carbonates occurs approximately near the lower boundary of the dark-humus horizon. In microdepressions, we observe an increase in the depth of secondary carbonates occurrence and the formation of clay-illuvial (argic) horizon leached from carbonates directly below the dark humus horizon due to additional inflow of surface runoff. Secondary carbonates (pseudomycelium) accumulate deeper. In Luvic Chernozems, the thickness of the clay-illuvial horizon with leached off carbonates is less than 50 cm; in Luvic Chernic Phaeozems, it exceeds 50 cm. Luvic Stagnic Chernic Phaeozems (Loamic, Pachic) are formed in the bottoms of balkas, especially in their middle and lower parts, and are characterized by the deepest leaching of carbonates and, often, by seasonal reducing conditions.

On the presented soil maps, regardless of the type of terrain, the areas of Luvic Stagnic Chernic Phaeozems may only neighbor the areas of Luvic Chernic Phaeozems, while the areas of zooturbated Haplic Chernozems may neighbor not only the undisturbed Haplic Chernozems but also Luvic Chernozems and even Luvic Chernic Phaeozems. The latter is explained by specific habits of burrowing animals. Their burrows (sleeping chambers at a depth of 1–3 m and tunnels) are less susceptible to strong moistening in the spring under convex elements of the microtopography. Animals feed on pulpy herbs, which grow in abundance in the microdepressions. Thus, the close proximity of strongly convex and concave elements of microtopography suggesting a minimum distance between the dwelling and feeding grounds is often optimal for burrowing animals.

On the southern slope, erosional and accumulative processes act as an additional factor in the soil cover patterns formation. As a result of erosion, the thickness of the humus layer decreases and often becomes less than 50 cm, which excludes the use of the Pachic qualifier. At the same time, the lower part of the profile is not subjected to significant changes. However, the carbonate-accumulative horizon formally comes closer to the surface. Under conditions of the close embedding of loesslike loams by low-permeable sediments, which is sometimes observed in the lower parts of the mesoslope, hard groundwater seasonally appears in the profile causing hydrogenic accumulation of secondary carbonates within its upper part.

Thus, in conditions of well-permeable loesslike loams of relatively high thickness, the aridity index of about 1.0 (fluctuations 0.7–1.2), and the deep occurrence of groundwater under the steppe mixed herb-grassy vegetation, the differentiation of soil cover patterns is due to two groups of processes. First – the redistribution of precipitation water by the elements of the meso and microtopography leading to differentiation of water percolation and, hence, the vertical migration and accumulation of labile carbonates and to the erosion of the surface horizon from convex landforms and accumulation of eroded soil material on the concave landforms. Second, the activity of burrowing animals ensuring mechanical mixing of the humus and carbonate-accumulative horizons and thus changing the parameters of the humus and carbonate soil profiles and the microtopography. The latter leads to the trigger effect on the redistribution of moisture. The agrogenic transformation of the soil cover leads to the increase in the role of erosional processes in shaping the soil cover patterns (especially on the slopes).

Figure 5a shows elementary soil cover patterns of the Central Chernozemic Nature Reserve and adjacent arable fields. Automorphic, automorphic-semihydromorphic, semihydromorphic, erosive, and semihydromorphic-erosive types of soil cover patterns are separated according to the soil composition.

Automorphic elementary soil cover patterns occupy elevated slightly inclined (up to 3°) or undulating interfluves. Their area is about 30% of the total area of the studied plot. Haplic Chernozems predominate; Luvic Chernozems and Luvic Chernic Phaeozems are supplementary soils. Automorphic-semihydromorphic elementary soil cover patterns with Luvic Stagnic Chernic Phaeozems and Luvic Greyzemic Stagnic Chernic Phaeozems are formed in the bottoms of large hollows with additional soil water supply from runoff flows. On the slopes, the soil cover has dendritic patterns of the erosive-suffosion type with Haplic Chernozem as dominant soils on the south-facing slope. Luvic Chernozem and/or Luvic Chernic Phaeozem with Luvic Stagnic Chernic Phaeozem predominate on the north-facing slope. These elementary soil cover patterns are complicated by Luvic Stagnic Chernic Phaeozems in the bottoms of erosional hollows and in the upper reaches of ravines. Slopes with arable lands are mostly eroded. Slightly, moderately, and strongly eroded analogues of all Chernozems and Phaeozems are formed on them. On the one hand, erosional processes change the topography of the territory with corresponding changes in the moisture redistribution. On the other hand, they partially erase the specificity of the natural soil combinations.

Elementary soil cover patterns on a large-scale soil map are mainly controlled by the dendritic patterns of the network of ravines and balkas. Automorphic and automorphic-semi-hydromorphic and hydromorphic elementary soil cover patterns predominate in the northern part of the plot with poorly dissected topography. Hydromorphic elementary soil cover patterns occur in the lower part of the slope and in the bottoms of the wettest hollows. Under conditions of steeper slopes of such hollows, the formation of semihydromorphic erosional elementary soil cover pattern is possible. With an increase in the degree of topography dissection (the central and southern parts of the plot), the share of erosional elementary soil cover patterns becomes significant, and the area of automorphic elementary soil cover patterns decreases. Slightly and moderately eroded soil cover patterns occur in the lower parts of the slope. Automorphic-semihydromorphic elementary soil cover patterns occupy small areas, and hydromorphic elementary soil cover patterns are virtually absent in the central and southern parts of the Kursk polygon.

Kirsanov polygon

The soil cover of the Kirsanov key polygons has a more diverse composition in comparison with the Kursk polygon. The soils belong to the three reference soil groups: Chernozems, Phaeozems, and Stagnosols. Stagnosols are specified by the presence of a mottled horizon with reduced zones outside aggregates and oxidized zones inside aggregates. There are Stagnosols with albic material in the soil profile. The formation of Stagnosols is associated with the long-termed surface waterlogging in the bottoms of large shallow closed depressions. As a rule, the profiles of Chernozems and Phaeozems have an argic horizon with the upper boundary at a depth of ≤100 cm (Luvic qualifier) and, sometimes, with retic properties. In some Chernozems and Phaeozems, there are features of seasonal reduced conditions in the form of iron-manganic nodules (Stagnic qualifier) and whitish silty and sandy skeletans on ped faces (Greyzemic qualifier). Calcic Chernozems are formed under the influence of groundwater saturated with calcium carbonates. The horizon containing carbonates in significant amounts (>15%) is formed at the depth of 80–100 cm.

The soil cover consists of Haplic Chernozems (Clayic, Aric, Oxyaquic), Luvic Chernozems (Clayic, Aric, Oxyaquic, Pachic), Luvic Retic Greyzemic Stagnic Chernic Phaeozems (Clayic, Aric), Luvic Retic Greyzemic Stagnic Phaeozems (Clayic, Aric), Luvic Chernic Phaeozem (Clayic, Aric, Oxyaquic, Pachic), Calcic Chernozems (Clayic, Aric, Oxyaquic, Pachic), and Eutric Luvic Albic Mollic Stagnosols (Clayic, Aric). Thus, hydromorphic and semihydromorphic soils predominate in the composition of the soil cover.

The soil cover pattern of slightly inclined interfluve plains dissected by ravines, balkas, and valleys of small rivers (Kirsanov-3 plot) consists of Haplic Chernozems and Luvic Chernozems forming irregularly shaped areas extending along the bottom of the hollows with Luvic Retic Greyzemic Stagnic Chernic Phaeozems and convex surfaces at the lower part of the short slope of the ravine (>5°) with eroded soils. Luvic Chernozems occupy concave elements of the microtopography and constitute less than 30% of the total plot area. The area of Luvic Greyzemic Stagnic Chernic Phaeozems is less than 5%.

There are no eroded soils on the slightly inclined poorly drained plain of plot Kirsanov-2. The share of Luvic Retic Greyzemic Stagnic Chernic Phaeozems reaches 25%. Uncoated silty and sandy grains are presented on ped faces in the lower part of the chernic horizon. Soil have distinct stagnic properties. Iron-manganic concentrations of up to 3 mm in diameter occur from the depth of 70–80 cm.

Rounded areas of Luvic Retic Greyzemic Stagnic Phaeozems are formed in large shallow closed depressions, where moisture stagnation may exceed two months (Akhtyrtsev et al. 1981). The soil profile includes the mollic horizon of 25–35 cm in tickness instead of the chernic horizon. The middle-profile horizon has retic and stagnic properties. Bluish gray humus coatings are abundant on ped faces. Iron-manganic pedofeatures are found within the entire soil profile, and their diameter reaches 5 mm. There are no carbonates in the soil profile.

Within the flat nondrained interfluve (Kirsanov-1 plot) with numerous microlows, the soil cover pattern is composed of Haplic Chernozems, Luvic Chernozems, and Luvic Retic Greyzemic Stagnic Chernic Phaeozems. Elementary soil areas have elongated oval, rounded, or irregular shapes. In the area of the poorly manifested hollow network, the low-contrasting soil combination of Haplic Chernozems, Luvic Chernozems, and Calcic Chernozems (Oxyaquic) is formed. Elementary areas of Calcic Chernozems (Oxyaquic) are confined to the bottoms of hollows with the groundwater depth of 1.5–2 m. These soils have a light-colored calcareous (carbonate-accumulative) horizon at the depths of 80–100 cm containing more than 15% $CaCO_3$ owing to the hydrogenic accumulation of carbonates from both lateral subsurface flows and the groundwater. In the underlying horizon, carbonate nodules with a diameter of 2 cm occur. Color patterns attesting to reduced conditions are not expressed in Calcic Chernozems (Oxyaquic) due to continuous flow of groundwater rich in carbonates.

Thus, under conditions of a flat poorly dissected interfluve with low-permeable parent materials and the aridity index of about 1, the leading factor in the formation and differentiation of soil combinations is the surface and subsurface water redistribution, including the transfer of surface runoff into the groundwater and the rise of the groundwater level under the microlows. Generally poor drainage

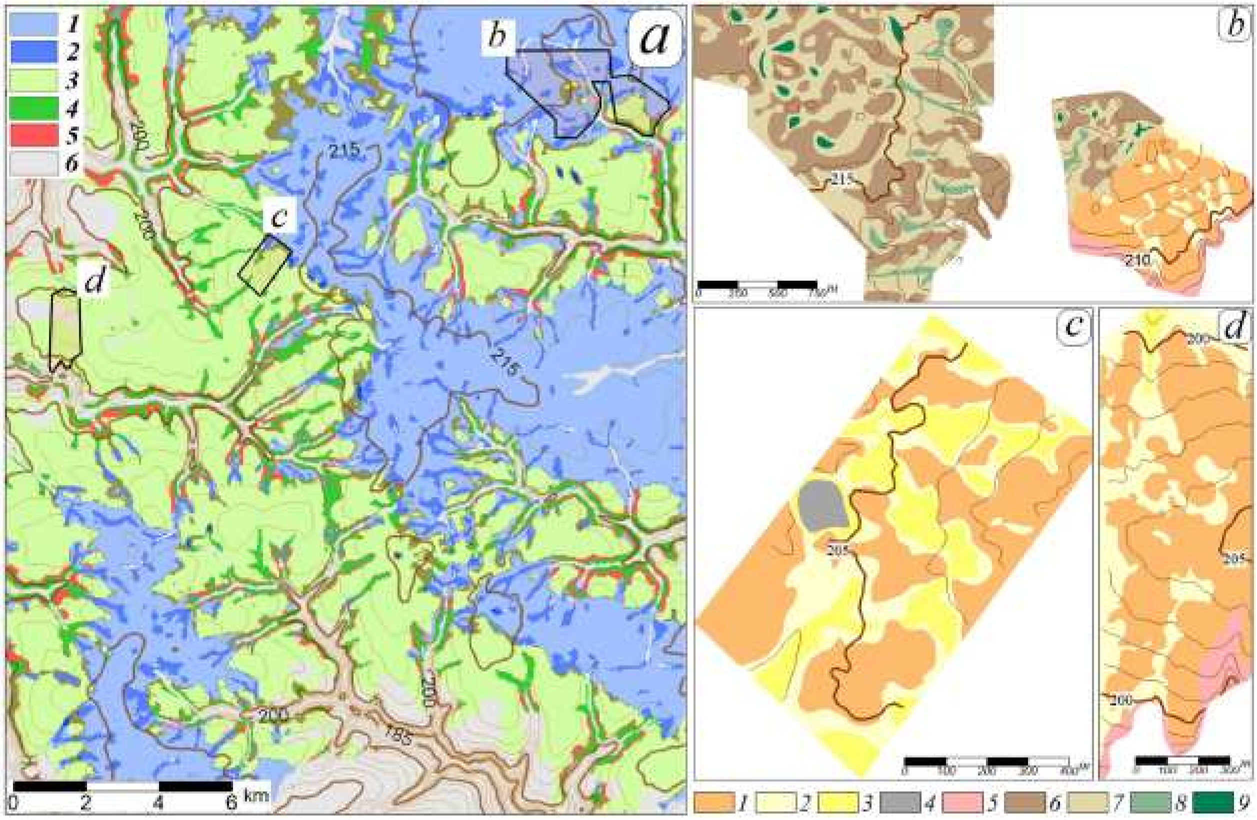

FIGURE 6. Soil cover patterns in the forest-steppe of the Volga Upland (Kirsanov polygon). Abbreviations of soil units are given according to IUSS Working Group WRB (2015). Components of soil combinations are listed in the decreasing order of their portion in the composition of soil combinations: (a) general view of the polygon and location of key plots; 1-CH-ha-ce.ai.oa.ph, CH-lv-ce.ai.oa.ph,PH-ch.st.gz.rt.lv-ce.ai,ST-mo.ab.lv.eu-ce.ai, 2- CH-ha-ce.ai.oa.ph, CH-lv-ce.ai.oa.ph, PH-ch.st.gz.rt.lv-ce.ai, 3-CH-ha-ce.ai.oa.ph,CH-lv-ce.ai.oa.ph, CH-lv-ce.ai.oa.ph, PH-ch.st.gz.rt.lv-ce.ai, 4-CH-lv-ce.ai.oa.ph, CH-lv-ce.ai.oa.ph, PH-ch.st.gz.rt.lv-ce.ai, CH-ha-ce.ai.oa.ph, 5-CH-ha-ce.ai.oa, CH-ha-ce.ai.oa.ph, 6-Not representative area (b) plot Kirsanov-1, (c) plot Kirsanov-2, (d) plot Kirsanov-3. Soils: 1-CH-ha-ce.ai.oa.ph, 2-CH-lv-ce.ai.oa.ph, 3-PH-ch.st.gz.rt.lv-ce.ai, 4-PH-st.gz.rt.lv-ce.ai, 5-CH-ha-ce.ai.oa, 6-CH-ha-ce.ai.oa.ph, 7-CH-lv-ce.ai.oa.ph and PH-ch.lv-ce.ai. oa.ph, 8-CH-cc-ce.ai. oa.ph, 9-ST-mo.ab.lv.eu-ce.ai

conditions and considerable density of microlows in the landscape result in the increase in the area of Luvic Retic Greyzemic Stagnic Chernic Phaeozems in the soil cover pattern. In the nondrained type of terrain, the areas of soils experiencing long-term surface waterlogging (Eutric Luvic Albic Mollic Stagnosols) increase.

Groundwater flows at a shallow depth in the hollows favor the formation of Calcic Chernozems (Oxyaquic). The transport of solid soil particles by water flows has a limited distribution within the studied plots owing to the general flatness of the topography.

Figure 6 shows a map of the elementary soil cover patterns of the Kirsanov polygon. There are five types of elementary soil cover patterns: two hydromorphic types, two semihydromorphic types, and one erosional type. Semihydromorphic soil combinations with Haplic Chernozems, Luvic Chernozems, and Luvic Retic Greyzemic Stagnic Chernic Phaeozems predominate. Hydromorphic soil combinations are confined mainly to broad flat interfluves complicated by microlows. These soil combinations include Eutric Luvic Albic Mollic Stagnosols (Clayic, Aric) in the bottoms of the microlows. These soils have the long-term stagnation of surface water. Interfluves with the indicated elementary soil cover patterns are dissected by a system of ravines and balkas of dendritic shape. The erosional type of soil combinations is confined to the steep slopes of ravines that occupy less than 5% of the studied area. These soil combinations usually include two soil components: Haplic Chernozems (Clayic, Aric, Oxyaquic) and Haplic Chernozems (Clayic, Aric, Oxyaquic, Pachic).

The Central Russian and Volga uplands differ from one another according to the composition and functioning of soil cover patterns at the local and regional levels. Under conditions of virgin landscapes on flat interfluves, water migration is the leading factor in differentiation of the soil cover patterns within Kursk and Kirsanov polygons.

At the Central Russian Upland, dominant soils are different kinds of Chernozems without stagnic properties. Water migration along the topography elements and the burrowers activity lead to the formation of the following elemental composition of the soil cover pattern: zooturbated Haplic Chernozems-Haplic Chernozems-Luvic Chernic Phaeozems-Luvic Stagnic Chernic Phaeozems. Intensive land use and high potential erosion are the reasons for the high (>50%) percent of eroded soils and the predominance of erosional soil combinations in the soil cover.

On the Volga Upland, semihydromorphic and hydromorphic analogues of Chernozems are formed because of the low hydraulic conductivity of parent materials, wide flat interfluves, lower degree of erosional dissection of the territory, and shallow depth of groundwater. The soils with stagnic properties occupy about 60% of the key plot. Elementary soil cover patterns consist of Haplic Chernozems, Luvic Chernozems, Luvic Chernic Phaeozems, and, additionally, Luvic Retic Greyzemic Stagnic Chernic Phaeozems and Eutric Luvic Albic Mollic Stagnosols.

Kamennaya Steppe polygon

In the Kamennaya Steppe area, 61 soil cover patterns have been identified; they differ in their composition, complexity, specificity of the micro- and mesotopography, parent materials and underlying sediments. The map of the soil cover patterns has been published (Khitrov and Cheverdin 2016) (http://www.jbks.ru/archive/issue-16/ article-2).

On flat interfluve areas with a poorly manifested microtopography and a relatively uniform layer of loesslike loams and clays of more than 2 m in thickness, a three-component low-contrasting soil combination of Haplic Chernozems (Clayic, Pachic), zooturbated Haplic Chernozems (Clayic, Pachic), and Luvic Chernozems (Clayic, Pachic) predominates (Khitrov and Loiko 2010). At present, due to a general rise of the groundwater table to a depth of 2–5 m in the agroforest landscape of the Kamennaya Steppe, reducing conditions occur at the depths of 130–200 cm in the spring and early summer. Then, they are replaced by oxidizing conditions with the formation of small iron nodules. More than 80% of the territory is used as arable land (supplementary qualifier Aric). The remaining part of the polygons is under the shelterbelt of 100–120 years in age and two large sections of the protected steppe that has not been plowed since 1882–1900.

The development of hollows, ravines, and balkas on the slope leads to the transformation of the low-contrasting three-component soil cover pattern into the linear or dendritic soil cover patterns with additional soils. In the bottoms of hollows and ravines, narrow (10–30 m) stripes of Luvic Chernozems (Clayic, Pachic, Stagnic) are formed. Luvic Vertic Chernozems (Clayic, Pachic, Stagnic) are formed on the slopes of some hollows (Khitrov, 2012). The areas between the hollows and ravines are occupied by the three-component soil combinations described above. Near the edges of hollows with good drainage conditions, the percent of zooturbated Chernozems increases.

Soils that experience seasonal (in spring and early summer) surface waterlogging or ponding are added to these components on the flat interfluves with clearly expressed deep (up to 1 m) closed depressions. Temporary ponding (from 10–20 days to 2 months) contributes to the formation of Luvic Retic Greyzemic Vertic Stagnic Chernic Phaeozems (Epiloamic, Endoclayic, Pachic). The profile of these soils consists of a thick (60–70 cm) humus horizon, the upper part of which corresponds to the chernic horizon. The lower part meets the criteria of the mollic horizon with whitish uncoated sand and silt particles on ped faces (qualifier Greyzemic). Then, there is a transitional horizon characterized by retic properties. From 75–85 cm, slickensides and wedge-shaped structure (vertic horizon) occur. There are also clayey coatings on prismatic aggregates (argic horizon) with manifested stagnic properties.

The differentiation of soil cover patterns is controlled by the mesotopography and lithological sequences of parent materials and underlying sediments. Eastern slope towards the Talovaya balka is relatively steep (2–4°, in some places up to 10°), and parent materials replace one another at short distances. Erosional, erosional-zonal, and semihydromorphic-erosional microcatenas are specific for the steepest areas (3°–10°) on the east-facing slope. West-facing slope is gentle and is characterized by the presence of saline and solonetzic soils.

Owing to the stratified bedding of Quaternary and older sediments at the Kamennaya Steppe polygon, relatively homogeneous in space yellowish brown loesslike clays and clay loams of more than 2 m in thickness on the flat interfluve alternate with the two-layered sediments; the upper yellowish-brown loesslike clay or clay loam is underlain by the cinnamonic-brown clay from the depth of 1–1.5 m. Such a lithological change is accompanied by the formation of carbonate pedofeatures in the form of whitish soft nodules (white eyes, beloglazka). Thus, Chernozems with the carbonate pseudomycelium are replaced by Chernozems with segregational forms of carbonates; according to the WRB, both soils are classified as Haplic Chernozems (Clayic, Pachic). The soil cover of the slope also includes zooturbated Chernozems, clay-illuvial Chernozems (Luvic Chernozems (Pachic)) and eroded variants of all these soils, for which the Pachic qualifier cannot be used (humus horizon is less than 50 cm).

Soils subjected to seasonal waterlogging and containing soluble salts are most often found at the altitudes from 185 to 180 m in the hollows and other concave parts of the slope. In these landforms, brown clay with low hydraulic conductivity occurs at the depth of 0.8–1.3 m under a layer of permeable yellowish brown loesslike clay loam and clay. Such soils may have various qualifiers: Haplic, Luvic, Vertic or Bathyvertic, Protosodic, and Protosalic. At the absolute altitudes below 180 m, mosaic soil cover patterns are formed due to the frequent alternation of parent materials (sands, colluvial clay loams, and redeposited moraines of different textures). At the foot of the eastern slope, the thickness of the humus horizons in soil increases.

South- and west-facing slopes are gentler. Their topography is complicated by the dense network of wide ravines passing into balkas. Clay-illuvial Chernozems with the secondary carbonates at the depth from 130 to 200 cm and more can be classified as Luvic Stagnic Chernic Phaeozems (Clayic, Pachic) and are developed in the bottoms of hollows and ravines underlain by permeable sediments.

The soils with seasonal and/or permanent gley or quasigley features, secondary salinization, solonetzicity, and vertigenesis are developed in the bottoms and/or on the slopes of wide valleys under conditions of shallow (<1–1.5 m) embedding by the dark brown and chocolate-colored low-permeable clay. Several groups of soil combinations exist in this area. Haplic Chernozems (Clayic, Pachic), zooturbated Haplic Chernozems (Clayic, Pachic), and Luvic Chernozems (Clayic, Pachic) are developed on the slopes of hollows and on the interfluve plain; Luvic Chernozems (Clayic, Pachic, Stagnic), Vertic Chernozems (Clayic, Pachic, Stagnic), Luvic Vertic Chernozems (Clayic, Pachic, Endoprotosalic, Protosodic, Stagnic), Luvic Stagnic Chernic Phaeozems (Clayic, Pachic), Luvic Glossic Mollic Stagnosols (Clayic, Humic, Endoprotosalic, Sodic), and Luvic Glossic Mollic Stagnosols (Clayic, Humic, Endoprotosalic, Sodic, Bathyvertic) are formed in the bottoms of hollows; solonetzic soil complexes appear within the lower part of the slope, where the set of soils includes Luvic Chernozems (Clayic, Pachic, Protosodic), Luvic Greyzemic Chernozems (Clayic, Pachic, Endoprotosalic, Protosodic, Stagnic), Salic Stagnic Solonetzes (Albic, Clayic, Columnic, Cutanic, Differentic, Humic), Nudinatric Vertic Stagnic Solonetzes (Clayic, Columnic, Cutanic, Humic), and Nudinatric Vertic Endosalic Stagnic Solonetzes (Clayic, Cutanic, Humic, Magnesic).

CONCLUSIONS

Against the background of traditional views on the zonal sequence of Chernozems on the East European Plain – podzolized chernozems (Luvic Greyzemic Chernic Phaeozems (Loamic or Clayic, Pachic)) → leached chernozems (Luvic Chernic Phaeozem (Pachic) or Luvic Chernozems (Pachic)) →typical chernozems with carbonate pseudomycelium (Haplic Chernozem (Pachic)) →ordinary chernozems with soft calcareous nodules (white eyes) (Haplic or Calcic Chernozem (Pachic)) →southern chernozems with a thinner humus layer and with soft calcareous nodules (Haplic or Calcic Chernozem (Loamic)) replacing one another from the north to the south – more detailed studies attest to the presence of diverse soil combinations forming specific soil cover patterns. Their composition, spatial organization, and functioning are determined by the particular combinations of soil-forming factors within a given area with the dominant role of (micro)topography, physical properties of parent material and the depth of the groundwater table. Our results can be applied in precision agriculture in forest-steppe areas to maximize crop yields and reduce environmental risk.

According to our findings, the spatial organization of the soil cover in the chernozemic zone of the East European Plain is characterized by the following regularities.

1. On flat interfluves and gentle slopes with a thick layer of loesslike clay loams and clays, low-contrasting soil combinations are composed of three soils: the background Haplic Chernozems (Loamic or Clayic, Pachic), zooturbated Haplic Chernozems (Loamic or Clayic, Pachic) with strongly mixed profile on the convex elements of microtopography and Luvic Chernozems (Loamic or Clayic, Pachic) within the concave elements of microtopography. The size of elementary soil areas varies from the tens of square meters to 1–5 ha. The soils differ in the distribution of carbonates in the profile owing to the digging activity of earth burrowers and the redistribution of water by the elements of the microtopography.
2. On steep slopes under arable fields, soil combinations with eroded soils marked by noticeable decrease in the thickness of the humus horizon are formed. The Pachic qualifier is not applicable to them, though it is a characteristic of natural Chernozems.
3. Close embedding (at a depth of 1–3 m) of the upper clay loamy mantle by poorly permeable sediments of different origins and/or poor drainage of flat watersheds are the factors controlling the appearance of seasonally over-moistened soils in the soil cover due to groundwater, temporarily perched water or surface` runoff water. As a result, Chernozems or Chernic Phaeozems with stagnic properties in different parts of the profile, or even Mollic Stagnosols appear in the soil cover patterns.
4. Local outcrops of swelling clays of different ages (from Quaternary to Jurassic) cause the formation of Bathyvertic Chernozems, Vertic Chernozems, Vertic Chernic Phaeozems, and/or Pellic Vertisols in soil combinations.
5. The presence of soluble salts sources in the landscape contributes to the development of solonetzic complexes consisting of Protosodic or Sodic Chernozems and various types of Solonetzes including Vertic Solonetzes.

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