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GENESIS AND GEOGRAPHY OF SOILS

Early Stages of the Evolution of Chernozems under Forest Vegetation (Belgorod Oblast)

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Abstract—We studied automorphic forest-steppe Luvic and Haplic Chernozems (Siltic/Clayic, Pachic) of the southern part of the Central Russian Upland (Belgorod region), which were covered with broadleaved forest vegetation at different times (from 25 to 75 years ago). The studies were carried out on an overgrowing fallow and the adjacent maple–ash shelterbelt and on an area of growth of a natural oak forest towards the virgin meadow steppe. The line of effervescence in the soil profiles descended by 12–25 cm during 60–75 years of the growth of forest vegetation on Chernozems. The average rate of carbonate carbon leaching from a 2-m soil layer reached 5 t/ha per decade. The humus horizon thickness increased by 7–13 cm. A decrease in the organic carbon storage was observed in the soil profiles during the first 25–30 years of the development of Chernozems under forest vegetation; in the following decades, the organic carbon storage increased. The soil organic matter in the upper part of the profiles (0–40 cm) was directionally enriched with fulvic acids, while the opposite tendency of an increase in the content of humic acids was observed in the middle part of the profiles (40–80 cm). The clay mobility increased in the Chernozems under forest vegetation, which is proved by an increase in the content of silty infillings in the studied chronosequence of Chernozems under tree stands of different ages (from 25 to 60–75 years) and by the appearance of clay–humus cutans in the soils under forest vegetation. The direction and staging of changes characterize the evolutionary transformation of Chernozems over time under the impact of forest vegetation. Soil changes were caused by changes in vegetation from herbaceous (meadow-steppe) to forest and the resulting changes in the hydrothermal regimes of soil formation. The staging of soil changes could be determined by the vegetation succession changes coupled with corresponding changes in the soil regimes in microclimatic conditions.

Keywords: soil carbon, shelterbelt, soil micromorphology, chronosequence, leached chernozems (Luvic Chernozems, Haplic Chernozems (Siltic/Clayic, Pachic))

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INTRODUCTION

The relationships between the forest and the steppe, soils of the forest genesis and chernozems have been studied for more than 120 years. Hypotheses about the natural advance of the forest over the steppe [16, 17, 24, 25], about the "wandering" of forests in steppe areas [12, 13], about the anthropogenic advance of the steppe onto the forest [23], and about the originality and old age of most of the forest and steppe areas in the forest-steppe zone [6, 20] have been suggested. In the light of new facts obtained in the course of archaeological studies and the development of the methods of paleogeographic reconstruction in the 20th century the idea of the climatogenic nature of the formation of the insular pattern of forest groves in the forest-steppe of the East European Plain has been affirmed. The main factor in the formation of forest-steppe landscapes and soils in their modern (natural) appearance was the cooling and moistening of the climate in the Subatlantic period of the Holocene, which led to the Late Holocene expansion of the forest vegetation to the south, as well as to the spread of forests from depressions in the erosional network (ravines and river terraces) to watershed surfaces, which resulted in the transformation of chernozems into gray forest soils in forested areas (previously steppe) [1, 2, 7, 9]. Recent studies have confirmed this trend of climate, vegetation, and soil changes in the Late Holocene [3, 4, 26, 27].

As follows from the results of soil-archaeological studies carried out using the method of soil chronosequences, the duration of the transformation of chernozems into gray forest soils as a result of the Late Holocene advance of the forest over the steppe varied from 1000 to 2000 years or more, depending on the lithological composition of soil-forming substrates. On sands and loamy sands, it proceeded faster than on loams and clays [26]. According to other sources, chernozems formed on heavy loesslike loams retain their main properties over 2000 years of being under broadleaved forest vegetation [19]. Based on the soil-archaeological studies carried out in different regions of the forest-steppe, it was established that, under more humid and cool conditions in the northern part of the forest-steppe zone, the evolutionary transformation of chernozems into gray forest soils occurred more intensively than in the south of the forest-steppe [27]. Recent studies have shown that the advance of forests onto the steppes was not a unidirectional process; in the Late Holocene, several long phases of recurrent aridization of the climate were noted, during which the steppe moved over the territories previously occupied by forests and the progradation of soils into chernozems was observed [4]. These results are based on a comparative study of the long chronosequences of buried and surface soils. Therefore, the features of the long-term (centennial) transformation of chernozems into gray forest soils can be considered well studied [2–4, 27].

Until recently, there have been practically no studies on the short-term effects of forest vegetation on chernozems, which could be identified with the initial stages of their change under forest. Such studies are of great fundamental and applied importance. Their fundamental nature is determined by the needs of the development of the theory of soil evolution and soil-forming processes. The applied aspect of such research is the need to obtain new information about the rate of change in the properties and fertility of chernozems under the influence of a phytogenic factor, which, in particular, is relevant for agroforestry reclamation of chernozem soils. In addition, in the forest-steppe of the Central Russian Upland, there is a long-term and stable natural growth of forests and artificial forest plantations over hayfields and pastures with chernozems on the slopes of ravines and in river valleys [33]. This advance of forest vegetation over large areas of chernozems requires soil-ecological monitoring.

The purpose of this study is to analyze the features of the transformation of automorphic meadow-steppe chernozems during the first decades of their development under forest vegetation. To achieve the goal, we applied a set of field and laboratory research methods. Special attention was paid to the choice of key sites for field work. The analysis of the results included graphical and statistical data processing and mapping techniques.

OBJECTS AND METHODS

For the study and comparative analysis of chernozems at different stages of development under woody vegetation, we selected areas, where forest vegetation settled on the meadow-steppe chernozems at different times. At the same time, background (not changed by forest) chernozems should have been present next to the forested plots. This method of conjugated study of background steppe soils and soils covered with forest vegetation at different times corresponds most closely to the method of soil chronosequences [10, 14]. In this particular case, we deal with soil phytochronosequences. Spatiotemporal series of changes in soil properties in response to the change in the vegetation cover were described earlier, in particular, by Jenny [32]. In our study, the search for suitable phytochronosequences of chernozems was aimed at finding some compact arrangement of the plots with background chernozems and their analogues under forest vegetation of different ages under conditions of maximum similarity of the topography and parent materials. Age boundaries within the soil chronosequences were established by analyzing large-scale maps of different times and remote sensing materials (historical-cartographic method of research and the method of repeated observations), as well as by counting annual rings of wood cores drilled in 4-fold repetition by Haglof increment borers in areas with forest vegetation of different ages. Forest stands aged 25, 30, 60, and 75 years were identified.

Soils were studied in deep and wide (1.8 × 1 × 2 m) pits, in which morphological description of the profile, determination of morphometric indicators (thickness of genetic horizons and depth of effervescence), and layer-by-layer soil sampling from each 20-cm layer to a depth of 2 m were performed. Layer-by-layer sampling was convenient for subsequent comparative analysis of soils at identical depths and layers, including the layer-by-layer calculation of the stocks of organic matter, carbonates, humus, and clay. Soil bulk density was determined in samples taken with steel rings of a known volume in three replicates from different depths throughout the soil profile. The particle-size distribution analysis was performed by the pipette (sedimentation) method with the soil pretreatment with sodium pyrophosphate (GOST (State Standard) 12536-2014).

The organic carbon content was determined by Tyurin's method in the TsINAO modification (GOST 26213-91). The actual acidity was studied by the potentiometric method (GOST 26423-85). Carbonate carbon was determined chromatographically, 1 h after the start of the reaction of a soil sample with a 10% HCl solution poured in excess into vessels tightly closed with rubber stoppers. The group composition of soil humus was determined layer by layer (every 20 cm) to a depth of 1 m in each studied soil profile using the Kononova–Bel'chikova method [18]. All soil analyzes were performed in a certified laboratory of the Federal State Budgetary Institution Belgorodsky Center of Agrochemical Service.

To study the micromorphological features of soil horizons and identify elementary soil-forming processes, undisturbed soil samples (soil monoliths) taken. The preparation of thin sections and their subsequent micromorphological description was performed in the Dokuchaev Soil Science Institute. The microstructure, organic matter features, composition of finely dispersed matter, pedofeatures, and soil microfabrics were described using an Olympus BX51 polarizing microscope with an Olympus DP26 digital camera and Stream Basic software.[1] Statistical parameters (mean, error of the mean, standard deviation, and coefficient of variation) were determined in the calculation of the thickness of soil horizons and the depth of effervescence based on the results of multiple ($n = 20$ in each soil pit) field measurements of depths along the side and front walls of the pits. The arithmetic mean, error of the mean, standard deviation, coefficient of variation were determined using the Statistica software package.

The layer-by-layer stocks of the organic carbon (C_{org}), carbonate carbon (C_{carb}), and clay (<0.001 mm) were calculated from data on their contents taking into account the bulk density of each soil layer.

The taxonomic position of soils was determined in accordance with the traditional soviet soil classification system [15] (in particular, for comparison examples from other sources) and the WRB system [31].

The objects of research were phytochronosequences of chernozems at two key sites in the center of the forest-steppe zone in the southern part of the Central Russian Upland. The first site was found in the south of Gubkin district of Belgorod oblast, 200 m east of the outskirts of the village of Stepnoe (Stepnoe site) and included a shelterbelt and the adjacent fallow. The second site was confined to the territory of the Yamskaya Steppe, one of the clusters sites of the Belogorye Nature Reserve in the northern part of Gubkin district, 40 km from the first site (Zapovednyi site) (Fig. 1). The sites are located on watershed surfaces with slope inclinations from 0° to 1.5°.

At the Stepnoe site, a multi-row 30-m-wide maple–ash shelterbelt was planted 60 years ago on the edge of an old-fallow meadow-steppe plot. Plowing on the fallow plot was performed before the mid-1950s. In the shelterbelt, ash-leaved maple (*Acer negundo*) and common ash (*Fraxinus excelsior*) grow in alternating rows (overall, five rows of trees). In the undergrowth, there are rare specimens of English oak (*Quercus robur*) and ash (*Fraxinus excelsior*). The undergrowth is locally represented by euonymus (*Euonymus verrucosus*). The projective cover of herbs varies from 0 to 10%; the herb layer is represented by wood meadow-grass (*Poa nemoralis*) and nettle (*Urtica dioica*) growing in separate patches. The shelterbelt is oriented from south to north; in the studied area, it occupies a watershed surface with a very slight slope to the west.

When comparing a modern satellite image with a topographic map of 1981, zones of growth of the forest shelterbelt over the adjacent fallow were revealed (Fig. 1a), which was used to study the soil chronosequence represented by the background soil on the old fallow (pit 1) and its analogues under 25- and 60-yr-old forest plantations (pits 2 and 3, respectively). The distance between the study points was 30–35 m (pits 1 and 3 were 63 m apart). The parent rocks are yellow-brown heavy loesslike carbonate loams underlain from a depth of 1.2–1.4 m by sandy loams and loamy sands of the alluvial genesis. The background soil is a medium-deep, medium-humus, clay loamy leached chernozem with the organic carbon content of 3.77% in the upper (0–20 cm) layer; the organic carbon stock in the 1-m layer is 24.8 kg/m^2.

At the Stepnoe site, the studied soil chronosequence is represented by the following soil varieties: the background soil is a medium-deep clay loamy leached chernozem on calcareous heavy loam underlain by sandy loam (Luvic Chernozem (Clayic, Pachic), pit 1); the soil under a 25-yr-old tree plantation is a medium-deep clay loamy leached chernozem on calcareous clay loam underlain by loamy sand and sandy loam (Luvic Chernozem (Clayic, Pachic), pit 2); the soil under the 60-yr-old shelterbelt is a deep clay loamy strongly leached chernozem on calcareous clay loam underlain by loamy sand (Luvic Chernozem (Clayic, Pachic), pit 3).

At the Zapovednyi site within a flat watershed of the reserved Yamskaya Steppe, a chronosequence of chernozems at the contact of the virgin grass–forb steppe and the forest tract Kotenevskie verkhi was studied. An old-growth (75-yr-old) forest grove consists of English oak (*Quercus robur*) with an admixture of wild pear (*Pyrus communis*). The breath height diameter of the trunks is 35–50 cm, and the height of the trees is 18–20 m. In the undergrowth, there are Norway maple (*Acer platanoides*), English oak (*Quercus robur*), common ash (*Fraxinus excelsior*); the shrub layer is represented by euonymus (*Euonymus*). A comparison of the topographic map of 1982 on a scale of 1 : 10000 and a modern satellite image (Fig. 1b) indicated that, since 1982, the edge of the forest grove has shifted over the adjacent steppe to a distance of 30–50 m. The area recently overgrown by trees includes common ash and English oak trees of 10–15 cm in trunk diameter and the height of 7–10 m. The shrub layer is represented by sparse specimens of *Euonymus verrucosus*. The border between the forest and the meadow steppe is marked by dense thickets of blackthorn (*Prunus spinosa*) in the form of a 3- to 6-m-wide strip.

[1] Micromorphological studies were performed with the use of equipment of the Collective Use Center “Functions and Properties of Soils and the Soil Cover” of the V.V. Dokuchaev Soil Science Institute.

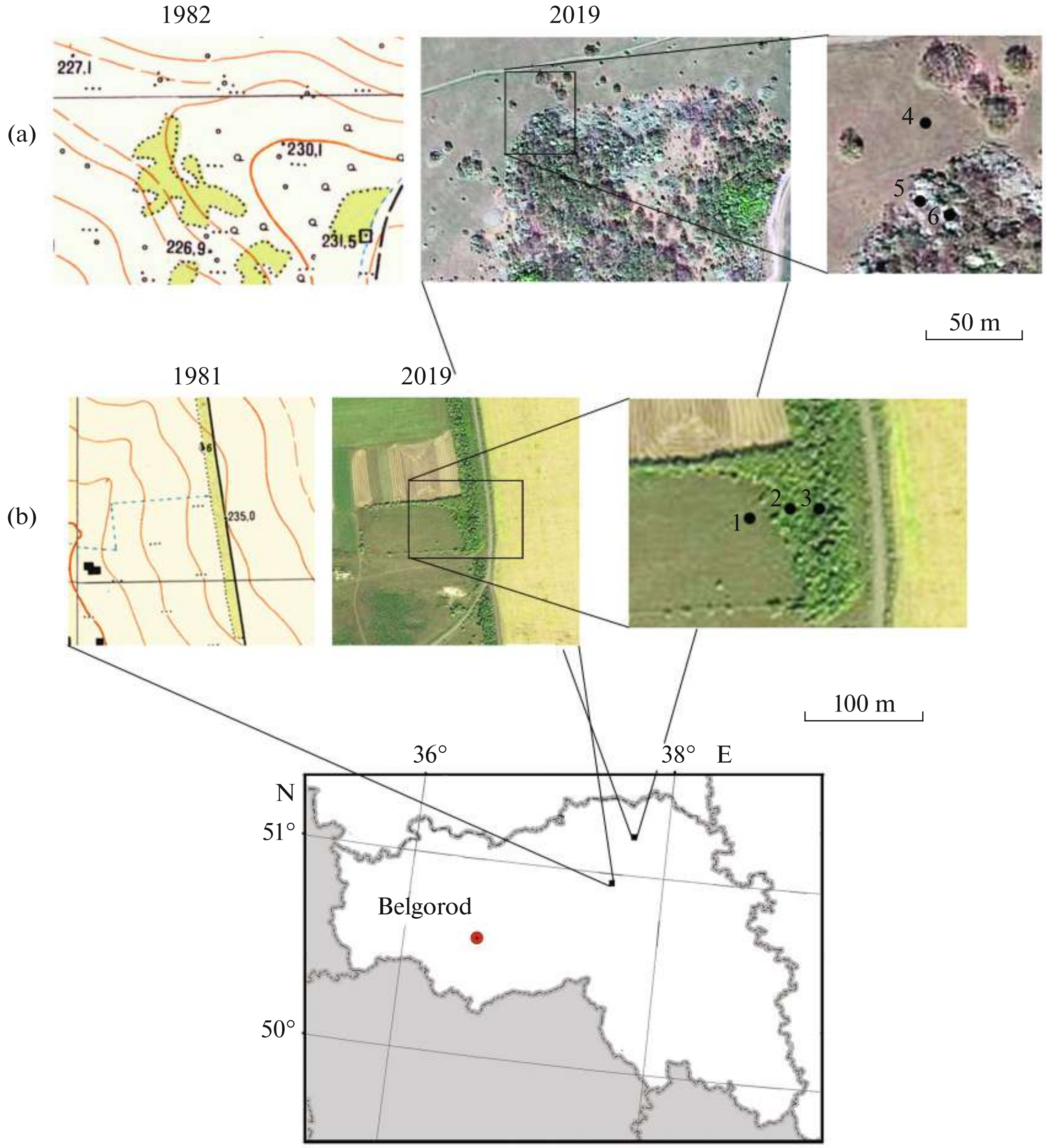

Fig. 1. Location of study sites: (a) Zapovednyi site and (b) Stepnoe site. The advance of forest vegetation over steppe was judged by comparing modern satellite images (2019) and large-scale topographic maps of 1981–1982. Location of studied pits is indicated by their numbers corresponding to the description in the text.

The soil-forming rocks in this area are represented by yellowish brown carbonate loesslike loams underlain at a depth of 1.2–1.5 m by ancient alluvial sands and loamy sands. The distance between the neighboring soil pits in this chronosequence (pit 4, background (steppe) soil; pit 5, under the forest; pit 6, under the forest) did not exceed 35 m; pits 4 and 6 were 70 m apart from one another. The background soil studied in pit 4 contains 4.61% C_{org} in the layer of 0–20 cm and is characterized by the Corg stock of 34.4 kg/m^2 in the 1-m layer.

At the Zapovednyi site, the background soil was identified as a medium-deep clay loamy typical chernozem on calcareous clay loam underlain by sandy loam (Haplic Chernozem (Siltic, Pachic), pit 4); the soil under the 30-yr-old forest, as a deep clay loamy leached chernozem on calcareous clay loam underlain by sandy loam (Luvic Chernozem (Siltic, Pachic), pit 5); and the soil under the 75-yr-old forest as a clay loamy leached chernozem on calcareous clay loam underlain by sandy loam (Luvic Chernozem (Siltic, Pachic), pit 6). The bedding of the calcareous clay loam by sandy loams is determined by a gradual increase in the proportion of the sand fraction in the lower part of the soil profiles; the upper boundary of the layer with an increased sand content has wavy shape without any spatial trend of changes; it lies at a depth of 100–120 cm.

Despite the similarity of the age of forest stands and the features of background soils and parent materials in the areas of the two studied soil phytochronosequences, the microclimatic conditions prevailing in these areas are not completely identical. In contrast to the Stepnoe site with a shelterbelt crossing an open area, at the Zapovednyi site chernozems could already be affected by the shadow effect of the nearby old-growth forest already in the first years of the formation of the soil phytochronosequence. Differences in the microclimatic conditions of the two studied soil phytochronosequences could affect the different intensity of soil-forming processes caused by the advance of forest vegetation over steppe chernozems.

The specificity of the study was determined by the complexity of the search for representative objects (automorphic steppe areas subjected to overgrowing by forest plantations) and some conventionality of the results of applying the soil chronosequence method associated with the spatial variability of soil properties.

RESULTS AND DISCUSSION

Morphological and micromorphological features of studied soils. The results of measurements of the thickness of soil horizons and the depth of effervescence are presented in Table 1. A common feature of the two sites is an increase in the depth of soil effervescence from 10% HCl with an increase in the age of forest plantations; a simultaneous increase in the thickness of humus horizons and the humus layer (A1 + A1B horizons at the Zapovednyi site and A1 + A1B + BA1 horizons at the Stepnoe site) takes place. When comparing the extreme members of the soil chronosequences (background soils and soils of long-term exposure under forest vegetation), the most pronounced differences were found for such characteristics as the thickness of humus horizons and the depth of effervescence (Table 1).

In addition, morphometric characteristics of the soils of the studied chronosequences attest to some other differences between them. Already at the initial stage of development under young (25–30-yr-old) forests, the initially homogeneous A1 horizon is subdivided into two subhorizons: $A1^{I}$ and $A1^{II}$. These subhorizons differ in their structure (the upper one is crumb (subangular blocky)–granular, while the lower one is granular–subangular blocky) and density (the upper subhorizon becomes loosened because of the presence of fine roots of herbs and especially trees in it, while the lower subhorizon remains dense, compacted).

In the upper and middle parts of the chernozem profiles under the forest, the features attesting to the mobility of humus-clay substances—glossy illuviation coatings on the surface of aggregates in the A1B, BA1, and B horizons—appear (pits 3 and 6, chernozems under old-growth forest stands at the Stepnoe and Zapovednyi sites).

Carbonate pedofeatures in the background soils are represented by whitish fine veins of carbonate pseudomycelium, small spots of "carbonate mold" (Bk, BCk horizons), and single hard calcareous nodules (Bk horizons). In the soils under forest vegetation, carbonate pseudomycelium in the lower part of Bk and in BCk horizons is being replaced by whitish calcareous tubes of up to 1–1.5 mm in thickness. Under older forests (60- and 75-yr-old), the frequency of occurrence of hard calcareous nodules in the BCk horizon increases.

The revealed changes in the morphological properties of chernozems under forest vegetation attest to a higher intensity of the humus-accumulative process (as judged from the increase in the thickness of humus horizons and humus soil layer and their darker color), on the one hand, and to a higher mobility of humus and clay substances (clay–humus coatings), on the other hand. The results of the morphological analysis are supplemented by the analysis of soil micromorphological properties.

At the Zapovednyi site, the humus horizons of chernozems under both meadow-steppe and forest communities are characterized by a very high degree of biogenic structuring, but the maximum degree of manifestation of this process is characteristic of the soil under the steppe. The humus horizons have a medium crumb (subangular blocky)–granular or granular–crumb structure with participation of coarser aggregates and a very dark (almost black) color owing to the high amount of humus coagulates with bridges between them. In the soils under the forest, in addition to humus coagulates, there are small areas with brown-colored humus represented mainly by humus "flakes" and very fine (about 1 μm) humus concentrations.

In the B horizon of the studied background (steppe) soil at a depth of 80–85 cm, the finely dispersed matter is of the humus–clay and clay–carbonate composition, while in the soils under the forest, only humus–clay and clay substances are present. Despite the great depth, the material of the horizons in this part of the profiles is strongly altered by soil fauna, and some parts of the soil mass are still noticeably stained with humus. Humus occurs in the form of microclods and "punctuations" (under the steppe) and microclods with bridges (in the humified loci of soils under the forest).

In the Bk horizon at a depth of 105–110 cm, humus matter in the background soil under the steppe is represented by "punctuations", while in the soils under the forest, by microclods and "punctuations." The maximum size and frequency of occurrence of humified loci sharply increase in the following sequence: soil under the steppe (up to 500 μm, single)—soil under a 30-year-old forest (400–2000 μm, single)—soil under a 75-year-old forest (200–2000 μm, about 50% of the section area).

Table 1. Thickness of genetic horizons and depth of effervescence in background chernozems and their analogues under forest stands of different ages (for each pit, $n = 20$), cm

Soils of the chronosequence	Horizon	*Lim*	$X \pm \delta_X$	δ	*V*, %
		Stepnoe site			
Background chernozem, pit 1	A1	29–36	32.4 ± 0.5	2.37	7.3
	A1B + BA1	28–35	31.6 ± 0.5	2.32	7.3
	A1 + A1B + BA1	60–68	64.0 ± 0.6	2.83	4.4
	B	23–38	28.9 ± 1.3	5.80	20.1
	BCk	22–44	32.2 ± 1.8	7.89	24.5
	Effervescence	85–97	91.3 ± 1.0	4.27	4.7
Chernozem under 25-yr-old forest, pit 2	A1	39–49	43.3 ± 0.6	2.87	6.6
	A1B + BA1	28–40	33.2 ± 0.9	4.08	12.3
	A1 + A1B + BA1	70–84	76.5 ± 0.9	4.09	5.3
	B	10–20	15.6 ± 0.8	3.56	22.8
	BCk	36–49	39.5 ± 0.8	3.63	9.2
	Effervescence	82–96	86.7 ± 1.0	4.55	5.2
Chernozem under 60-yr-old forest, pit 3	A1	38–52	44.7 ± 1.1	4.97	11.1
	A1B + BA1	28–43	37.3 ± 0.9	4.22	11.3
	A1 + A1B + BA1	74–89	82.0 ± 1.0	4.52	5.5
	B	13–25	19.4 ± 0.9	4.00	20.6
	BCk	20–36	30.1 ± 1.3	5.92	19.7
	Effervescence	109–127	115.9 ± 1.2	5.43	4.7
		Zapovednyi site			
Background chernozem, pit 4	A1	35–50	42.8 ± 1.2	5.45	12.7
	A1B	11–42	29.6 ± 1.8	7.84	26.5
	A1 + A1B	57–86	71.8 ± 1.5	6.91	9.6
	Bk	22–51	31.2 ± 1.9	8.38	26.9
	BCk	13–45	28.6 ± 2.2	9.99	34.9
	Effervescence	68–88	80.1 ± 1.1	4.96	6.2
Chernozem under 30-yr-old forest, pit 5	A1	44–61	52.8 ± 1.1	4.76	9.0
	A1B	15–36	23.1 ± 1.0	4.38	19.0
	A1 + A1B	70–82	75.9 ± 0.8	3.54	4.7
	B	13–26	19.6 ± 0.8	3.59	18.3
	BCk	15–27	20.9 ± 0.8	3.50	16.7
	Effervescence	83–97	91.3 ± 0.8	3.63	4.0
Chernozem under 75-yr-old forest, pit 6	A1	43–58	49.6 ± 0.9	3.98	8.0
	A1B	16–31	24.0 ± 0.9	4.09	17.0
	A1 + A1B	65–84	73.6 ± 1.0	4.30	5.8
	B	14–46	30.4 ± 1.8	8.05	26.5
	BCk	12–34	22.1 ± 1.5	6.82	30.9
	Effervescence	88–95	91.6 ± 0.6	2.58	2.8

At the Zapovednyi key site, microfeatures attesting to a gradual increase in the mobility of a finely dispersed substance have been observed. Thus, in the background soil, there are no clay films on mineral grains in the lower part of humus horizons (40–45 cm), fragmentary films appear on mineral grains under a young forest at this depth; in the soil under a 75-year-old forest, clay coatings on mineral grains are continuous; there are also clay–humus coatings and infillings in pores (~2 μm thick). In the underlying horizons (80–85 cm) of chernozems, both under young and old forest, this feature is enhanced: at a depth of 105–110 cm, multilayer clay films are already found, which are absent in the background meadow-steppe chernozem.

Similar tendencies were revealed for the Stepnoe site. Here, in the layer of 15–20 cm, the microstructure of the humus horizons of all compared soils slightly differs in the chronosequence. The humus horizon is characterized by the high degree of aggregation and porosity typical of chernozems [8, 21, 29] and by intensive impregnation of the bulk soil mass with humus. With an increase in the age of forest, there is a regular increase in the frequency of occurrence of semidecomposed plant residues. In the lower part of the humus horizons (30–35 cm), zones of varying degrees of impregnation with humus begin to occur, and their area increases in the sequence: soil under the fallow—soil under the 25-yr-old forest—soil under the 60-yr-old forest. A similar pattern is also observed in deeper horizons (at a depth of 65–70 cm): in the background chernozem and in the soil under the 25-yr-old forest, humus-impregnated soil matter occupies about 50% of the thin section area, while in the soil under the 60-yr-old forest, it occupies about 70% of the thin section area. In the B horizons at a depth of 100–105 cm, the size and area of humified zones decrease in the following order: soil under the steppe (200–600 μm, ~5% of the thin section area)—soil under a 25-yr-old forest (200–8000 μm, up to 5% of the thin section area)—soil under the 60-yr-old forest (humified loci are absent).

At the Stepnoe site, as well as at the Zapovednyi site, an increase in mobility of finely dispersed matter in the soils of the chronosequence was noted according to the following changes. At a depth of 30–35 cm in the soil on the meadow-steppe fallow, clay coatings on pore walls and on aggregate faces are virtually absent; they appear under the 25-yr-old forest (single, 1–2 μm in thickness) and are better expressed in the soil under the 60-yr-old forest (up to 10 units per thin section area, up to 5 μm in thickness). Silty infillings were diagnosed in all the studied soils. However, their number increases in the sequence: soil under the fallow—soil under the 25-yr-old forest—soil under the 60-yr-old forest. At a depth of 65–70 cm in the soil under the 25-yr-old forest, silty infillings are about 1.5 times larger than those in the background steppe chernozem (600 and 400 μm, respectively) and occupy a relatively small area (up to 10% of the thin section area). In the soil under the 60-yr-old forest, the infillings are even larger (up to 1000 μm) and occupy the largest area (up to 25% of the thin section area). Their specific feature is the noticeable reworking of the material by soil meso- and microfauna. In both soils under the forest, clay coating on the surface of soil aggregates and pores were identified. Their number and degree of expression (integrity, thickness) increase from the soil under the 25-yr-old forest to the soil under the 60-yr-old forest (from 5–10 to 20 μm). The effects of the influence of forest vegetation on the processes of soil formation identified at the two key sites using micromorphological diagnostics of soils are shown in Fig. 2.

Particle-size distribution. According to the particle-size distribution data, the studied soils are classified as heavy loams (clay loams). However, soils of the Zapovednyi site are generally characterized by a somewhat coarser texture in comparison with soils of the Stepnoe site (Table 2). At both sites, the coarsening of the soil texture (an increase in the content of sand) occurs at a depth of 100–120 cm. This reflects the lithological discontinuity: a relatively thin layer of loess-like loam is underlain by sediments of a coarser texture (sandy loam and loamy sand) in the layer of 140–200 cm (Table 2). In this regard, the analysis of the profile distribution of the clay fraction was carried out only for the upper soil meter. The upper boundary of the underlying sediment is characterized by insignificant (within 10–20 cm) variation over the entire study area at both sites, which, in our opinion, could not significantly affect the particle-size distribution in the overlying soil-forming substrate.

Micromorphological studies have not identified the features attesting to the removal of clay from the upper soil layers. At the same time, a number of properties, such as an increase in the occurrence of silty infillings in the studied chronosequences from background chernozems to chernozems under the old forest stands and the appearance of clay–humus coatings in the soils under forest indicate an increase in the degree of mobility of finely dispersed matter in chernozems under the influence of forest vegetation.

According to the particle-size distribution data and our calculations, the uppermost 20-cm-thick soil layers under the forest (at both sites) are somewhat depleted of clay (Table 3). The development of this process in time is indicated by the greatest differences in the clay stock between the soils under the old (60- and 75-yr-old) forests and the soils under younger (25- and 30-yr-old) forests and under steppe (fallow). At both sites, the soils under young and old-growth forests display a tendency for clay accumulation in the layers deeper than 20 cm (Tables 3 and 4). The depletion of clay from the upper layers of automorphic chernozems under forest shelterbelts, as compared with the chernozems of adjacent plowland, was noted earlier [28].

According to Aleksandrovskii [2], who compared dark gray forest soils transitional to chernozems buried under kurgans and modern soddy-podzolic soils in the forest zone of the Republic of Mari El, in about 3200–3300 years, a zone of clay removal under the impact of forest vegetation was formed in a layer of 0–45 cm; the loss of clay from this layer reached about 8% of the mass of the mineral part of the soil. If we take the average bulk density of this layer as 1.2 g/cm^3, then the total removal of clay could reach 43 kg/m^2, and the average rate of clay removal was about 13 kg/m^2 over 1000 years. Researchers also studied chernozems

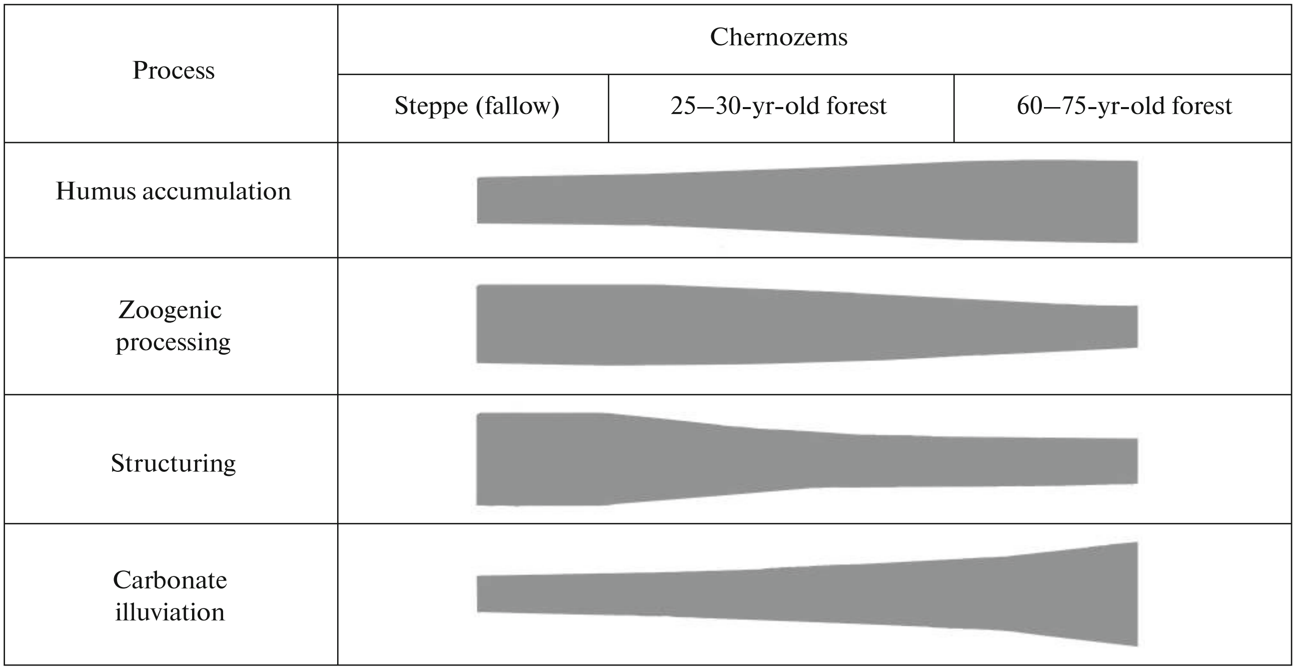

Fig. 2. Manifestation of elementary soil-forming processes in the compared soils of the chronosequences (averaged from the results of micromorphological studies of soils from the Zapovednyi and Stepnoe sites).

under the steppe and forest on the territory of the Alekhin Central Chernozemic Reserve and noted a number of differences between them: an increased thickness of the humus layer in chernozems under the forest, deeper levels of carbonate occurrence in them, and clearly manifested illuviation coatings in the B horizon, which were absent in chernozems under the steppe [19]. However, differences in the profile distribution of clay in the compared soils were not identified [19]. These examples allow us to assume low rates of the development of the eluvial–illuvial differentiation of chernozems under the impact of forest vegetation encroaching over the former steppe. According to our study, in 75 years under the forest, chernozems may lose up to a third or even a half of their initial clay reserves in the layer of 0–20 cm. This value seems to be overestimated and can be explained by the spatial variability in the clay content and stocks. Additional studies are required to estimate the rate of clay loss from the upper horizons of chernozems under the impact of forest vegetation.

Humus and carbonate profiles. The two sites display a staged nature of changes in the stocks of organic matter, which is especially pronounced at the Zapovednyi site: during the first 25–30 years of the development of chernozems under forest, a weak tendency for a decrease in the C_{org} stocks in the upper 1-m-thick soil layer was observed; on average, it was from 29.6 to 26.3 kg/m^2. For the 2-m-thick soil layer, the clay stock also decreased from 36.1 to 31.4 kg/m^2. In the following decades (under the 60- and 75-yr-old forest stands), the C_{org} stocks in the soils increased, on average, up to 30.5 kg/m^2 (0–1 m) and 36.2 kg/m^2 (0–200 cm) (Table 5, Fig. 3). At the second stage of growth of C_{org} reserves, the C_{org} stock under the 60-yr-old forest at the Stepnoe site even exceeded the C_{org} stock value in the background steppe chernozem; at the Zapovednyi site, it did not reach the level of the background chernozem.

As noted above, the history of the development of forest plantations at the two sites was somewhat different: at the Stepnoe site, the shelterbelt was planted in an open area; at the Zapovednyi site, a young forest formed next to an old-growth forest massif. This caused differences in the intensity of soil-forming processes.

Previous studies demonstrated that 55-yr-old shelterbelts in the south of the Central Russian Upland contribute to an increase in the humus content of a 1-m-thick layer of chernozem under them [30]. The results obtained for the Stepnoe site (where soils under a shelterbelt of similar age were studied) are additional confirmation of this phenomenon.

At the same time, at the Zapovednyi site, the humus stock in the chernozem under the old-growth fragment of the forest advancing over the adjacent steppe turned out to be less than the background value, which requires explanation.

Different environmental conditions for the growth of forest stands affect the differences in their vitality, which, in turn, can be one of the factors in the formation of different trends in humus formation and humus accumulation processes under the canopy of forest vegetation. Under the shelterbelt, vitality of the old-

Table 2. Particle-size distribution data

Layer, cm	Fraction size, mm; fraction content, %							
	1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01	>0.01
Stepnoe site, pit 1 (background)								
0–20	7.02	1.60	32.44	10.20	6.32	42.43	58.95	41.05
20–40	6.86	0.64	33.69	12.96	11.80	38.76	58.81	41.19
40–60	5.90	4.39	32.51	9.48	11.67	36.05	57.21	42.79
60–80	7.28	2.59	34.97	5.00	10.55	34.74	50.16	49.84
80–100	7.74	4.85	29.62	3.87	3.01	35.34	47.80	52.20
100–120	6.80	5.29	31.51	2.17	3.16	34.61	46.40	53.60
120–140	20.48	23.26	15.01	2.76	3.78	34.71	41.25	58.75
140–160	32.29	23.99	10.60	2.15	11.05	19.93	33.16	76.84
160–180	23.99	11.67	23.72	6.11	14.46	20.05	40.62	59.38
180–200	52.20	20.98	0.20	2.28	5.57	18.77	26.62	73.38
Stepnoe site, pit 2 (25-yr-old forest)								
0–20	9.82	4.39	27.11	10.65	8.84	36.44	55.93	44.07
20–40	9.89	2.07	29.80	11.21	11.18	35.85	58.24	41.76
40–60	13.31	0.82	29.45	12.91	8.87	34.64	56.42	43.58
60–80	30.54	1.45	27.54	13.41	10.95	36.11	60.47	39.53
80–100	9.79	4.47	27.99	8.94	11.83	36.98	57.75	42.25
100–120	34.32	4.06	22.65	3.95	6.47	28.55	38.97	61.03
120–140	65.24	5.13	7.70	0.31	4.18	17.44	21.93	78.07
140–160	78.49	2.66	2.02	4.33	2.77	9.73	16.83	83.17
160–180	71.74	5.92	3.28	4.00	1.43	13.63	19.07	80.93
180–200	72.12	3.19	5.58	0.25	4.73	14.13	19.11	80.89
Stepnoe site, pit 3 (60-yr-old forest)								
0–20	3.46	3.93	34.27	15.24	13.75	29.34	58.34	41.66
20–40	3.95	1.91	32.44	14.93	12.14	34.61	61.69	38.31
40–60	2.37	1.35	35.00	11.88	13.14	36.26	61.27	38.73
60–80	2.01	0.72	36.52	11.77	13.03	35.95	60.75	39.25
80–100	1.61	1.58	34.48	8.04	13.74	40.55	62.32	37.68
100–120	3.28	2.02	30.15	7.49	16.80	40.26	64.55	35.45
120–140	12.86	6.56	24.64	8.87	10.83	36.24	55.93	44.07
140–160	22.90	20.23	12.34	0.41	12.50	31.62	44.52	55.48
160–180	31.49	27.64	8.52	1.98	6.19	24.18	32.35	67.65
180–200	34.14	6.12	31.70	0.66	5.64	21.74	28.04	71.96
Zapovednyi site, pit 4 (background)								
0–20	4.28	12.75	39.80	9.89	18.93	14.35	43.17	56.83
20–40	2.51	10.75	39.64	10.79	21.88	14.42	47.10	52.90
40–60	2.08	6.75	39.32	10.00	22.77	19.07	51.84	48.16
60–80	1.49	4.65	39.04	10.70	22.53	21.60	54.83	45.17
80–100	1.58	6.39	34.79	11.04	23.87	22.33	57.24	42.76
100–120	1.71	7.36	36.29	7.94	23.97	22.73	54.64	45.36
120–140	2.50	14.03	31.81	7.05	24.61	20.00	51.66	48.34
140–160	5.76	16.88	28.10	12.21	15.01	22.04	49.26	50.74
160–180	7.87	27.22	13.61	1.96	10.16	39.18	51.29	48.71
180–200	5.16	16.13	25.72	2.58	8.26	42.15	52.99	47.01

Table 2. (Contd.)

Layer, cm	Fraction size, mm; fraction content, %							
	1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01	>0.01
Zapovednyi site, pit 5 (30-yr-old forest)								
0–20	2.21	12.66	42.70	9.02	21.26	12.16	42.44	57.56
20–40	3.34	12.69	35.56	10.39	19.66	18.36	48.41	51.59
40–60	1.70	11.76	34.07	11.23	17.73	23.51	52.47	47.53
60–80	1.26	8.04	36.13	9.77	19.21	25.60	54.58	45.42
80–100	1.46	8.67	34.82	10.87	21.75	22.42	55.05	44.95
100–120	2.88	27.03	19.62	9.14	20.62	20.71	50.47	49.53
120–140	3.57	43.49	14.84	5.83	12.70	19.57	38.10	61.90
140–160	3.21	38.85	14.27	14.01	6.46	23.20	43.66	56.34
160–180	5.03	47.05	9.86	6.81	3.51	27.74	38.05	61.95
180–200	7.26	23.08	19.69	4.04	11.25	34.68	49.97	50.03
Zapovednyi site, pit 6 (75-yr-old forest)								
0–20	7.48	23.99	37.16	9.92	14.61	6.84	31.37	68.63
20–40	6.20	18.04	30.21	11.42	17.11	17.02	45.55	54.45
40–60	5.72	16.93	28.56	11.90	17.12	19.77	48.79	51.21
60–80	5.45	18.61	26.41	11.47	13.31	24.74	49.53	50.47
80–100	4.85	18.17	29.04	9.68	14.56	23.70	47.94	52.06
100–120	3.87	24.77	23.34	3.80	20.11	24.11	48.02	51.98
120–140	6.51	41.98	16.95	2.23	16.14	16.19	34.56	65.44
140–160	6.52	50.62	11.03	2.86	4.55	24.44	31.81	68.19
160–180	7.46	35.47	16.35	4.99	7.13	28.58	40.71	59.29
180–200	7.13	25.51	21.14	7.18	7.34	31.70	46.22	53.78

Table 3. Contents (%)/stocks (kg/m^2) of clay in the soils of studied chronosequences

Layer, cm	Zapovednyi site			Stepnoe site		
	background	30-yr-old forest	75-yr-old forest	background	25-yr-old forest	60-yr-old forest
0–20	14.3/28.9	12.2/19.5	6.8/13.7	42.4/83.9	36.4/75.7	29.3/62.1
20–40	14.4/33.4	18.4/36.1	17.0/43.9	38.8/81.5	34.9/81.7	34.6/87.4
40–60	19.1/46.6	23.5/50.3	19.8/53.9	36.1/83.0	35.3/89.0	36.3/94.8
60–80	21.6/54.4	25.6/58.9	24.7/67.2	34.7/89.5	36.1/95.3	36.0/94.7
80–100	22.3/58.4	22.4/55.1	23.7/63.5	35.3/100.3	37.0/102.1	40.6/108.5

Table 4. Changes in the stocks of clay in separate soil layers in the studied soil chronosequences, kg/m^2

Layer, cm	Zapovednyi site			Stepnoe site		
	background	30-yr-old forest	75-yr-old forest	background	25-yr-old forest	60-yr-old forest
0–20	0	–9.4	–15.2	0	–8.2	–21.8
20–40	0	+2.7	+10.5	0	+0.2	+5.9
40–60	0	+3.7	+7.3	0	+6.0	+11.8
60–80	0	+4.5	+12.8	0	+5.8	+5.2
80–100	0	–3.3	+5.1	0	+1.8	+8.2

Table 5. Properties of soils studied at the Stepnoe and Zapovednyi sites (C_{org} and C_{carb}, % of soil mass)

Layer, cm	pH water	Bulk density, g/cm^3	C_{org}		C_{carb}		pH water %	Bulk density, g/cm^3	C_{org}		C_{carb}	
			%	t/ha	%	t/ha			%	t/ha	%	t/ha
	Stepnoe site, pit 1 (background)						Zapovednyi site, pit 4 (background)					
0–20	6.5	0.99	3.77	74.6	0	0	7.4	1.01	4.61	93.1	0	0
20–40	6.7	1.05	2.84	59.6	0	0	7.3	1.16	3.71	86.1	0	0
40–60	6.8	1.15	1.97	45.3	0	0	7.4	1.22	2.73	66.6	0	0
60–80	6.9	1.29	1.39	35.9	0	0	7.8	1.26	2.15	54.2	0.14	3.4
80–100	8.3	1.42	1.16	32.9	0.38	10.9	8,4	1.31	1.68	44.0	0.85	22.1
100–120	8.6	1.40	0.64	17.9	1.47	41.2	8.5	1.37	0.99	27.1	1.28	35.1
120–140	8.6	1.68	0.41	13.8	0.74	24.7	8.5	1.46	0.41	12.0	1.06	31.1
140–160	8.7	1.87	0.35	13.1	0.52	19.4	8.7	1.55	0.35	10.9	0.79	24.5
160–180	8.6	1.90	0.29	11.0	0.68	25.9	8.7	1.62	0.29	9.4	0.95	30.9
180–200	8.7	1.90	0.23	8.7	0.11	4.1	8.7	1.68	0.17	5.7	0.79	26.6
	Stepnoe site, pit 2 (25-yr-old forest)						Zapovednyi site, pit 5 (30-yr-old forest)					
0–20	6.9	1.04	3.63	75.5	0	0	6.4	0.80	5.13	82.1	0	0
20–40	6.3	1.17	2.81	65.8	0	0	6.4	0.98	3.39	66.4	0	0
40–60	6.5	1.26	1.91	48.1	0	0	6.4	1.07	2.55	54.6	0	0
60–80	7.1	1.32	1.39	36.7	0.11	2.9	6.6	1.15	1.86	42.8	0	0
80–100	8.4	1.38	0.81	22.4	1.17	32.4	8.2	1.23	1.28	31.5	0.52	12.7
100–120	8.7	1.47	0.58	17.1	1.42	41.7	8.7	1.29	0,58	15.0	1.34	34.5
120–140	8.4	1.56	0.41	12.8	0.79	24.7	8.6	1.37	0.35	9.6	0.74	20.2
140–160	8.6	1.65	0.35	11.6	0.27	9.0	8.5	1.45	0.29	8.4	0.35	10.3
160–180	8.8	1.72	0.23	7.9	0.08	2.8	8.8	1.52	0.23	7.0	0.41	12.4
180–200	8.2	1.76	0.17	6.0	0.08	2.9	8.5	1.54	0.17	5.2	0.71	21.8
	Stepnoe site, pit 3 (60-yr-old forest)						Zapovednyi site, pit 6 (75-yr-old forest)					
0–20	7.1	1.06	4.00	84.8	0	0	6.2	1.01	4.50	90.9	0	0
20–40	6.7	1.22	3.19	77.8	0	0	5.9	1.29	2.90	74.8	0	0
40–60	6.8	1.32	2.84	75.0	0	0	6.3	1.36	2.15	58.5	0	0
60–80	6.9	1.33	1.90	47.9	0	0	6.4	1.36	1.45	39.4	0	0
80–100	7.0	1.38	1.10	30.4	0	0	8.1	1.34	1.10	29.5	0.27	7.3
100–120	8.4	1.48	0.46	13.6	0.65	19.4	8.4	1.35	0.75	20.3	1.23	33.1
120–140	8.5	1.58	0.41	13.0	1.28	40.5	8.6	1.42	0.41	11.6	0.65	18.6
140–160	8.5	1.65	0.35	11.6	0.95	31.5	8.5	1.54	0.34	10.5	0.46	14.3
160–180	8.7	1.69	0.29	9.8	0.38	12.9	8.3	1.61	0.29	9.3	0.63	20.2
180–200	8.6	1.73	0.23	8.0	0.30	10.4	8.4	1.66	0.23	7.6	0.65	21.7

growth forest stand is weakened in comparison with the corresponding forest studied at the Zapovednyi site. Visually, this is expressed by a higher degree of littering of the soil surface by the remains of trees and shrubs and dead tree trunks under the shelterbelt (Fig. 4). An increased proportion of dead aboveground and underground plant residues in the soil of the shelterbelt could be a factor favoring a more active accumulation of organic carbon in this soil.

The staged nature of changes in the stocks of organic matter in chernozems under the impact of broadleaved forest vegetation found in our study is probably explained from the standpoint of the physiology of forest ecosystems and the changes that occur during the formation of forest stands. At the first stage of a young growing forest stand located in the area bordering the steppe, its barrier function of snow retention begins to be realized. Therefore, soil wetting after the snowmelt noticeably increases (this phenomenon has been well studied for agroforestry landscapes of the steppe zone [5]). A greater accumulation of moisture contributes to the intensification of the leaching pro-

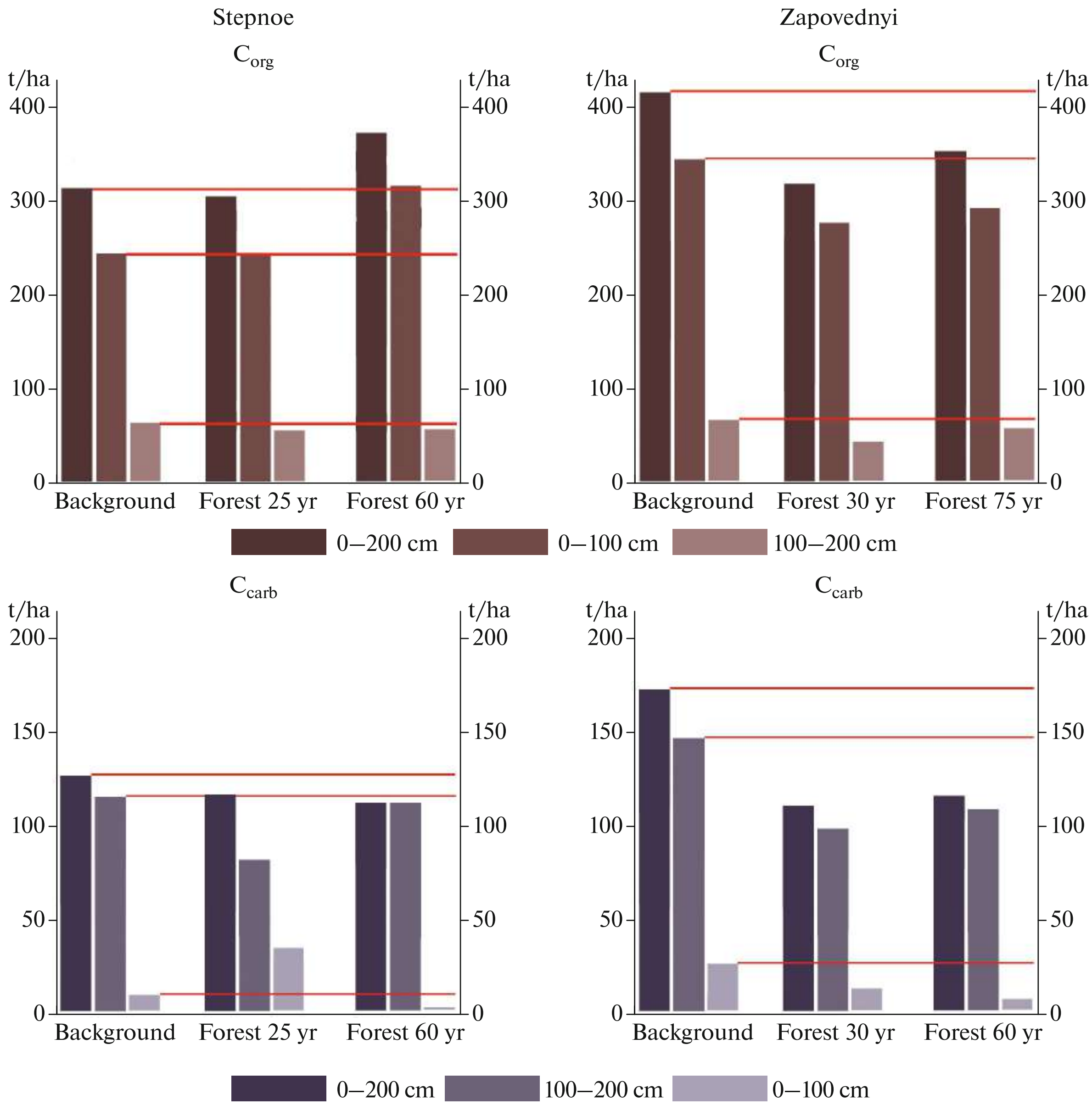

Fig. 3. Stocks of the carbon of humus and carbonates in separate layers of chernozems of phytochronosequences studied at the Stepnoe and Zapovednyi sites.

cess and the downward migration of the labile part of the soil organic matter. A relatively small amount of dead aboveground plant mass and plant roots enter the soil at this stage due to the youth of the forest ecosystem. Part of the soil organic matter inherited from the meadow-steppe stage of soil formation is mineralized, and the humus stock in the soil somewhat decreases. At the second stage, under a well-formed forest phytocenosis, the snow retention function is weakened due to the fact that this forest area is no longer at the outskirts of the shelterbelt; it is found at a certain distance from the forest/steppe border. A new strip of space bordering the steppe is occupied by young growing forest, which now performs the main function of snow retention. Therefore, soil moisture at the second stage of forest stand development is likely to decrease. This is facilitated by the fact that a mature (60–75 yr) stand requires more moisture, and root desiccation during the growing season dries out the soil more intensively. At the considered second stage of the development of forest vegetation, the volume of ground and underground plant falloff probably increases due to the weakening of the vitality of trees, when the mature tree stand becomes more affected by diseases, which can positively affect the balance of soil humus.

Staged changes in the stocks of organic matter in the studied phytochronosequences of chernozems are accompanied by a change in its qualitative composi-

(a) (b)

Fig. 4. Soil surface under the canopy of old-growth tree stands at the (a) Stepnoe and (b) Zapovednyi sites. In photo (a), there is a noticeable amount of tree waste as an indicator of reduced vitality of the stand compared to a fragment of natural forest in the photo (b).

tion (Table 6), which was previously noted in the micromorphological study of soils. The background chernozems of the two studied sites are characterized by the humate type of humus in the upper horizons, which is in line with traditional ideas about the qualitative composition of humus in chernozems [11]. In the upper part (0–20 cm) of the background chernozems, the Cha : Cfa ratio is 2.2–2.3; it gradually decreases downwards to about 0.8–0.9 in the layer of 80–100 cm (Table 6, Fig. 5). In chernozems under the forest, the soil humus in the upper horizon (0–20 cm) is noticeably enriched in fulvic acids: Cha : Cfa is 1.8–2.0.

The second important feature of the change in the group composition of humus in chernozems under the impact of forest vegetation is a tendency for an increase in the relative content of humic acids in the middle part of the soil profile (40–80 cm). At the Stepnoe site, under the shelterbelt, the development of this process in time is clearly manifested, while at the Zapovednyi site, an increase in the content of humic acids in the layer of 40–80 cm is detected only at the beginning of forest soil formation (under a 30-yr-old forest stand). Then, this process is replaced by an increase in the share of fulvic acids. It is possible that the established differences are due to a somewhat longer duration of forest pedogenesis at the Zapovednyi site compared to the Stepnoe site.

The main factor in the spatiotemporal changes in the group composition of humus in chernozems under forest vegetation may be a change in soil hydrothermal regimes. In a cooler (and wetter) forest environment, downward migration of substances begins to develop under the forest canopy, including the movement of humic acid components, as previously noted by other researchers [19, 22].

The analysis of the evolutionary changes in chernozems under the influence of forest vegetation is supplemented by a comparative characterization of the carbonate profiles of the soils. According to the results of our study, the depletion of the C_{carb} under 60- and 75-yr-old forest stands takes place at both sites. The main changes in the carbonate profiles of soils took place during the first 25–30 years of forest growth; later, the stabilization of C_{carb} stocks is observed. The average intensity of carbonate removal from a 2-m-thick soil layer (as judged from the difference between the background steppe chernozem and the chernozems under forest) is 0.2 kg/m^2 per decade at the Stepnoe site and 0.8 kg/m^2 per decade at the Zapovednyi site. This difference may be due to the initial differences in the stocks of carbonates in the soil profiles: at the Zapovednyi site, they were initially higher (for the layer of 0–2 m, 17.4 kg/m^2 C_{carb}), while at the Stepnoe site,

Table 6. Group composition of humus in the soils of the Stepnoe and Zapovednyi key sites

Depth, cm	C_{org}	C_{ha}	C_{fa}	C_{humin}	C_{ha}/C_{fa}
	%				
Stepnoe site, pit 1 (background)					
0–20	3.77	1.54	0.68	1.55	2.26
20–40	2.84	1.25	0.57	1.02	2.19
40–60	1.97	0.72	0.49	0.76	1.47
60–80	1.39	0.46	0.49	0.44	0.95
80–100	1.16	0.34	0.43	0.40	0.79
Stepnoe site, pit 2 (25-yr-old forest)					
0–20	3.63	1.44	0.77	1.42	1.88
20–40	2.81	1.30	0.61	0.91	2.14
40–60	1.91	0.82	0.47	0.63	1.74
60–80	1.39	0.46	0.47	0.46	0.98
80–100	0.81	0.24	0.28	0.29	0.87
Stepnoe site, pit 3 (60-yr-old forest)					
0–20	4.00	1.49	0.85	1.66	1.75
20–40	3.19	1.39	0.67	1.13	2.09
40–60	2.84	1.30	0.67	0.88	1.94
60–80	1.90	0.67	0.51	0.72	1.32
80–100	1.10	0.37	0.39	0.34	0.93
Zapovednyi site, pit 4 (background)					
0–20	4.61	1.68	0.72	2.21	2.33
20–40	3.71	1.34	0.63	1.74	2.15
40–60	2.73	1.01	0.53	1.20	1.92
60–80	2.15	0.77	0.61	0.78	1.27
80–100	1.68	0.48	0.51	0.69	0.94
Zapovednyi site, pit 5 (30-yr-old forest)					
0–20	5.13	1.63	0.83	2.67	1.97
20–40	3.39	1.25	0.59	1.56	2.13
40–60	2.55	1.01	0.50	1.04	2.00
60–80	1.86	0.72	0.53	0.61	1.35
80–100	1.28	0.38	0.49	0.41	0.79
Zapovednyi site, pit 6 (75-yr-old forest)					
0–20	4.50	1.68	0.85	1.97	1.97
20–40	2.90	1.25	0.62	1.03	2.02
40–60	2.15	0.86	0.54	0.74	1.59
60–80	1.45	0.48	0.41	0.56	1.22
80–100	1.10	0.33	0.34	0.37	0.87

they were lower (12.6 kg/m^2). Over the 60–75 years of forest soil formation, as a result of the new hydrothermal regime, the evolution of carbonate profiles at both sites led to the formation of chernozems with close stocks of carbonates in the two-meter soil layer: 11.5 kg/m^2 C_{carb}.

At the microlevel, there is a decrease in the diversity of carbonate features at depths of 100–110 cm in the BCk horizons in the sequence: background soils—soils under 25- and 30-yr-old forests—soils under 60- and 75-yr-old forests.

At the Stepnoe site, sparite infillings predominate in the background soil, lublinite coatings predominate in the soil under the young forest, and no carbonate pedofeatures are present in the soil under the old forest at a depth of 100–110 cm. At the Zapovednyi site, the

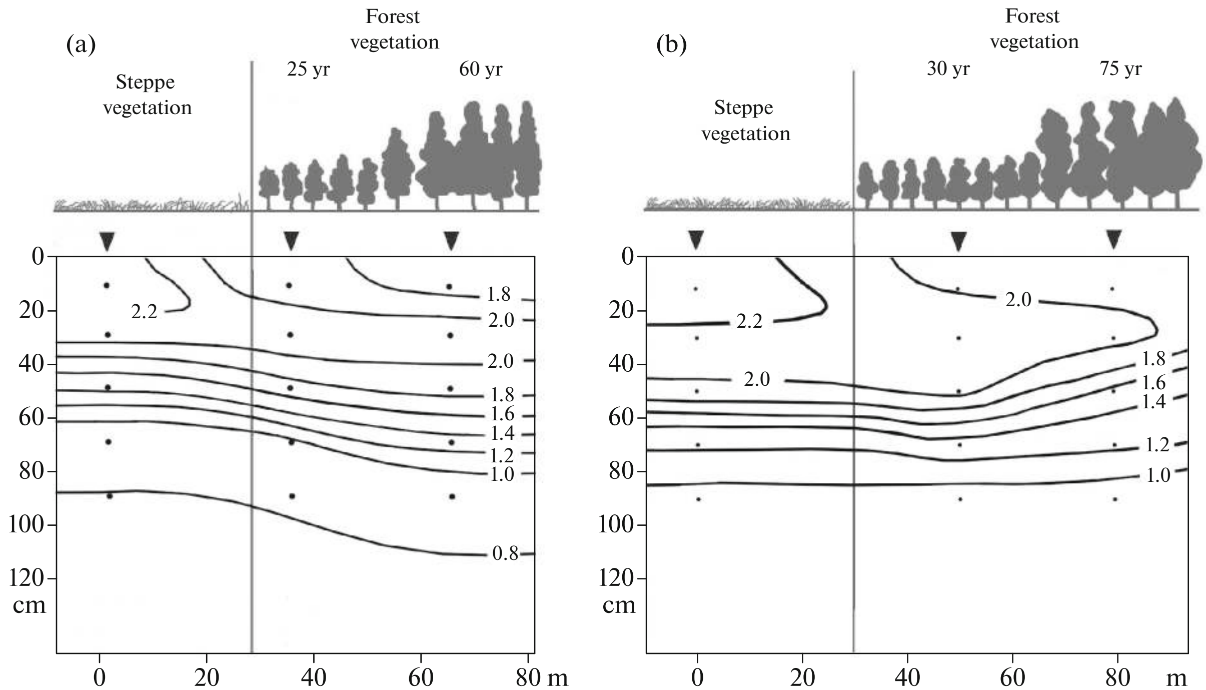

Fig. 5. Isolines of the C_{ha}/C_{fa} ratio in the studied chronosequences of chernozems at the (a) Stepnoe and (b) Zapovednyi sites.

background soil is dominated by lublinite and micritic coatings, the soil under the young forest is dominated by sparite infillings and micritic coatings, and only sparite infillings are found in the soil under the old forest. In all the soils studied, at a depth of 100–110 cm, carbonate nodules occur singly and are relatively small (200–800 μm). At the Zapovednyi site, in the soil under a 75-yr-old forest, a zone of modern formation of carbonate nodules was diagnosed by the heterogeneity of the material surrounding the pore space [21]: carbonate solutions are pulled up to the walls of the pores, which leads to the depletion of carbonates from the surrounding material (at a small distance from the pores).

Earlier, an increase in the diversity of carbonate pedofeatures in forest chernozems in comparison with meadow-steppe chernozems of the Alekhin Central Chernozemic Reserve was noted [19]. Thus, the fate of carbonates in chernozems under the impact of forest vegetation remains a debatable problem.

CONCLUSIONS

On the basis of a comparative analysis of the soil profiles of the two studied chronosequences represented by automorphic background medium-deep clay loamy chernozems and their analogues under broadleaved forest plantations of different ages, certain changes in a number of soil features and soil forming processes have been identified.

(1) During the first decades of the development of steppe chernozems under forest vegetation, noticeable changes in morphological and micromorphological properties occur in the soils. The thickness of humus horizons increases by 10–13 cm. The line of effervescence descends by 12–25 cm. Thus, the initial leached chernozems become transformed into strongly leached chernozems, and typical chernozems are transformed into leached chernozems. The initially homogeneous A1 horizon is subdivided into two subhorizons: $A1^{I}$ and $A1^{II}$. These subhorizons differ in their structure, bulk density, and saturation with roots. In chernozems under forest, features of the vertical migration of substances appear in the form of glossy illuviation coatings on the surface of aggregates; under the oldest (75-yr-old) forest, thin chocolate-brown illuviation coatings appear in the B horizon. Micromorphological analysis revealed changes in a number of soil-forming processes in the studied soil chronosequences: an increase in the degree of humus accumulation, the depth of biogenic processing, and intrahorizon mobilization of clay-humus finely dispersed matter. Carbonate pedofeatures at the microlevel demonstrate an increase in the root uplift of the soil solution under natural forest vegetation against the background of a general long-term trend of carbonate leaching from the soil profiles.

(2) The average intensity of carbonate removal from the two-meter thickness of chernozems, which were under forest vegetation for 60–75 years, varied within 2–8 (average 5) t/ha per decade. The evolution

of carbonate profiles was accompanied by regular changes in the forms of carbonate pedofeatures. Carbonate pseudomycelium, often found in the background meadow-steppe chernozems, is replaced by whitish calcitic tubes in the soils under forest vegetation. According to morphological diagnostics, a decrease in the diversity of carbonate pedofeatures is noted in the soils of the studied chronosequence in the BCk horizon. In the meadow-steppe (background) chernozems, carbonate pedofeatures in this horizon are represented by hard and loose nodules, intergrowths of crystals in pores, sparite infillings, and micritic cutans; in the chernozems under forest, only intergrowths of crystals and hard carbonate nodules have been identified.

(3) The growth of broadleaved forest vegetation on chernozems is accompanied by changes in the quantitative characteristics and qualitative composition of soil organic matter. For the two sites under consideration, a staged nature of changes in the organic matter stocks has been established: during the first 25–30 years, a decrease in the stocks of organic carbon is observed in their profiles under the impact of forest vegetation; in subsequent decades, the organic carbon stocks under forest tend to increase. The reason for this may be a change in the properties of forest stands as they form and a change in the intensity of the death of aboveground and underground organs of trees and shrubs. In chernozems under forest plantations, the humus of the upper part of the profiles (0–40 cm) is directionally enriched in fulvic acids, while the opposite trend is observed in the middle part of the profiles (40–80 cm), i.e., an increase in the humic content of organic matter. This feature of the C_{ha}/C_{fa} distribution in the soil profile brings the chernozems under forest vegetation closer to the type of gray forest soils.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. L. Aleksandrovskii, *Evolution of East European Soils in the Holocene* (Nauka, Moscow, 1983) [in Russian].
2. A. L. Aleksandrovskii, "Evolution of soils of Eastern Europe on the border of forest and steppe," in *Natural and Anthropogenic Evolution of Soils* (Pushchino, 1988), pp. 82–94.
3. A. L. Aleksandrovskii and E. I. Aleksandrovskaya, *Soil Evolution and the Environment* (Nauka, Moscow, 2005) [in Russian].
4. A. L. Aleksandrovskii, Yu. G. Chendev, and M. A. Trubitsyn, "Paleosol indicators of variability of ecological conditions in the central forest-steppe in the Late Holocene," Izv. Ross. Akad. Nauk, Ser. Geogr., No. 6, 87–99 (2011).
5. E. A. Afanas'eva, *Water-Salt Balance of Ordinary and Southern Chernozems of the Southeast of the European Part of the USSR* (Nauka, Moscow, 1980) [in Russian].
6. B. P. Akhtyrtsev, *Gray Forest Soils of Central Russia* (Voronezh State Univ., Voronezh, 1979) [in Russian].
7. L. S. Berg, *Climate and Life* (Geografgiz, Moscow, 1947) [in Russian].
8. T. L. Bystritskaya and M. I. Gerasimova, "The annual cycle of the modern chernozem process," Pochvovedenie, No. 6, 5–16 (1988).
9. N. B. Vernander, "Origin and properties of gray forest soils of the western part of the USSR," in *Studies in the Field of Soil Genesis* (Academy of Sciences of the USSR, Moscow, 1963), pp. 164–183.
10. A. N. Gennadiev, "Study of pedogenesis by chronoseries method (by the example of the soils of the Elbrus region)," Pochvovedenie, No. 12, 33–43 (1978).
11. A. N. Gennadiev and M. A. Glazovskaya, *Geography of Soils with Principles of Soil Science* (Vysshaya Shkola, Moscow, 2005) [in Russian].
12. G. E. Grosset, *Relationship between Forest and Steppe within the Forest-Steppe Belt of Eastern Europe* (Voronezh, 1930) [in Russian].
13. P. S. Denisov, *Soils of Voronezh and Kursk Oblasts and Their Reaction on Use of Agricultural Technology* (Voronezh. Obl. Knizhn. Isd., Voronezh, 1935) [in Russian].
14. I. V. Ivanov an A. L. Aleksandrovskii, *Methods for Analysis of Evolution and Age of Soils* (Pushchino, 1984) [in Russian].
15. *Classification and Diagnostics of Soils of the USSR* (Kolos, Moscow, 1977) [in Russian].
16. S. I. Korzhinskii, "The northern border of the chernozem-steppe region of the eastern strip of European Russia in botanical-geographical and soil terms," Tr. O-va Estestvoispyt. Imper. Kazan. Univ. **22** (6), (1891).
17. P. A. Kostychev, "Relationship between soils and certain plant formations," in *Proceedings of the VIII Cogr. of Russian Naturalists and Physicians* (St. Petersburg, 1890), pp. 37–60.
18. P. P. Krechetov and T. M. Dianova, *Soil Chemistry: Analytical Analysis* (Moscow, 2009) [in Russian].
19. N. Ya. Margolina, A. L. Aleksandrovskii, B. A. Il'ichev, A. E. Cherkinskii, and O. A. Chichagova, *Age and Evolution of Chernozems* (Nauka, Moscow, 1988) [in Russian].
20. F. N. Mil'kov, *Physical Geography: Theory about Landscape and Geographical Zonality* (Voronezh State Univ., Voronezh, 1986) [in Russian].
21. A. N. Polyakov and E. A. Yarilova, "The main features of microstructure of chernozems of the Central Chernozem regions," Pochvovedenie, No. 5, 99–109 (1978).
22. V. V. Ponomareva and T. A. Plotnikova, *Humus and Pedogenesis* (Nauka, Leningrad, 1980) [in Russian].
23. V. I. Taliev, "Humans as a botanical-geographic factor," Nauchn. Obozr., No. 11, 42–61 (1902).
24. G. I. Tanfil'ev, "Prehistoric steppes of European Russia," in *Land Science* (Nauka, Moscow, 1896), pp. 73–92.

25. I. V. Tyurin, "Genesis and classification of forest-steppe and "forest" soils," Uch. Zap. Kazan. Univ., Nos. 3–4, 429–462 (1930).
26. Yu. G. Chendev, *Evolution of Forest-Steppe Soils of the Central Russian Upland in the Holocene* (GEOS, Moscow, 2008) [in Russian].
27. Yu. G. Chendev, A. L. Aleksandrovskii, O. S. Khokhlova, M. I. Dergacheva, A. N. Petin, A. N. Golotvin, V. A. Sarapulkin, G. L. Zemtsov, and S. V. Uvarkin, "Evolution of forest pedogenesis in the south of the forest-steppe of the Central Russian Upland in the Late Holocene," Eurasian Soil Sci. **50**, 1–13 (2017). https://doi.org/10.1134/S1064229317010033
28. Yu. G. Chendev, A. N. Gennadiev, S. V. Lukin, T. J. Sauer, E. A. Zazdravnykh, V. G. Belevantsev, and M. A. Smirnova, "Change of forest–steppe chernozems under the influence of shelterbelts in the south of the Central Russian Upland," Eurasian Soil Sci. **53**, 1033–1045 (2020). https://doi.org/10.1134/S1064229320080037
29. E. A. Yarilova, "Micromorphology of chernozems," in *Chernozems of the USSR* (Kolos, Moscow, 1974), Vol. 1, pp. 156–173.
30. Yu. Chendev, A. Gennadiev, T. Sauer, E. Terekhin, and S. Matveev, "Forests advancements to grasslands and their influence on soil formation: forest steppe of the Central Russian Upland," IOP Conf. Ser.: Earth Environ. Sci. **392**, 012003 (2019). https://doi.org/10.1088/1755-1315/392/1/012003
31. IUSS Working Group WRB, *World Reference Base for Soil Resources 2014, Update 2015, International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, World Soil Resources Reports No. 106* (UN Food and Agriculture Organization, Rome, 2015.
32. H. Jenny, *Factors of Soil Formation: A System of Quantitative Pedology* (McGraw-Hill, New York, 1941).
33. E. A. Terekhin and Yu. G. Chendev, "Satellite-derived spatiotemporal variations of forest cover in southern forest-steppe, the Central Russian Upland," Contemp. Probl. Ecol. **12**, 780–786 (2019). https://doi.org/10.1134/S1995425519070102

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