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GENESIS AND GEOGRAPHY OF SOILS

Change of Forest–Steppe Chernozems under the Influence of Shelterbelts in the South of the Central Russian Upland

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Abstract—The results of a comprehensive study of soils under a 30-m-wide five-row oak shelterbelt of meridional orientation and on the adjacent arable fields of the agroforestry landscape in typical forest-steppe of Belgorod oblast are discussed. Background soils are medium-deep light clayey leached chernozems (Luvic Chernozems) on calcareous loesslike heavy loam. As a result of tree growth during the past 50 years (age of the shelterbelt), certain changes in the intensity and direction of soil-forming processes have taken place in soils of both the shelterbelt and the adjacent arable land. Data on the contents and stocks of the clay (<0.001 mm) and fine silt (<0.005–0.01 mm) fractions in the soil profile under the shelterbelt attest to the development of its textural differentiation. The accumulation of sodium and magnesium in soil water extracts is detected in the deep (200–400 cm) layer of this soil. Adjacent arable soils contain less carbonates than soils under the shelterbelt; the removal of carbonates from the layers of 0–200 and 0–300 cm is estimated at 57 and 84 t/ha, respectively. The topsoil (0–20 cm) under the shelterbelt significantly differs from the topsoil of the adjacent arable land in a lower bulk density, lower stocks of clay (<0.001 mm) and physical clay (<0.01 mm), and higher stocks of C_{org}. The influence of the shelterbelt on the properties of adjacent arable soils can be traced to a distance of 50–60 m from the shelterbelt edges. The significant quantitative differences are seen in the clay stocks.

Keywords: Belgorod oblast, agroforestry, bulk density, organic carbon, calcium, nitrogen, potassium, phosphorus, Chernozems, soil transformation

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INTRODUCTION

Soil degradation in agrolandscapes is one of the most acute environmental and economic problems of our time [23, 29]. To control it, a set of measures have been suggested, among which agroforestry planning of the territory occupies one of the highly important places. Agroforestry is considered one of the most efficient ways to control wind and water erosion of arable soils and to increase crop yields [1, 4, 5, 14]. Agroforestry in northern Eurasia has a long and successful history of implementation in agricultural activities in different natural zones. However, at present, insufficient attention is given to the study of the role of agroforestry in increasing land productivity in Russia; a particularly large decline in interest has taken place in the post-Soviet period [5].

One of the most pressing issues is the assessment of the influence of shelterbelts on changes in the morphological, chemical, physical, and other soil properties [1, 5, 9, 14, 17, 21, 22, 24, 30, 32].

Beginning with the studies of Tumin [20] in the Kamennaya Steppe, the opinions of researchers about the influence of shelterbelts on soils have been rather controversial. Thus, some scientists argue that the humus content of chernozems and Mollisols increases under the shelterbelts [20, 27, 34]. At the same time, there are facts of less obvious transformation of chernozems in the zones of shelterbelt influence [6, 7, 14, 16]. In some publications, not only positive but also negative impact of shelterbelts on soils and the environment is noted. Thus, according to some researchers, shelterbelts both on interfluves and in hollows of the gully network may cause waterlogging of landscapes up to the appearance of strongly waterlogged areas (mochars) [17, 22]. There is a lack of information and divergent opinions on some other issues of the response of chernozems to agroforestry, e.g., on the impact area of the shelterbelts on soils [1, 4, 9, 11]; on the nature of changes in physical properties of chernozems, including their texture, under shelterbelts [10, 15, 19]; and on the influence of shelterbelts on the salt budget of chernozems [24, 25]. In this regard, further studies aimed at identifying and analyzing changes in chernozems owing to the influence of long-term functioning of tree plantations are relevant. In our opinion, a comprehensive study of a wide range of properties of soils in the impact zone of shelterbelts is promising.

The aim of this study is to identify and analyze the direction and spatial patterns of the influence of shelterbelts on the properties of forest-steppe chernozems of the Central Russian Upland.

OBJECTS AND METHODS

Studies were carried out in the central part of the East European Plain, in Yakovlevskii district of Belgorod Oblast. The climate of the research area is moderately continental. The mean annual air temperature is +7°C, the mean July temperature is +20°C, and the mean January temperature is –6°C. The annual precipitation is 550–600 mm [12]. The aridity index calculated according to Sapozhnikova (with differential account for precipitation of the warm and cold seasons) equals 0.9 [13].

The chosen shelterbelt bordered on arable land on both sides and was oriented from south to north, so that the aspect-related impact on the adjacent arable soils was leveled. The shelterbelt was planted on a flat interfluve with a height of 208–209 m a.s.l. It consisted of five rows of oak trees with a total width of about 30 m; its age was estimated at 50 years according to counting of annual rings in tree cores (extracted with a Haglof borer).

The shelterbelt was planted in the late 1960s on a previously plowed area as indicated by some features of the soils under the shelterbelt. These soils are characterized by the increased bulk density in the layer of 20–40 cm corresponding to the previously existing plowpan with deteriorated soil structure and the appearance of coarse blocks and clods.

Soil management technologies on the adjacent arable fields have been subjected to certain changes over time. According to the Belgorod Center of Agrochemical Service, small amounts (on average, 4–5 t/ha per year) of organic fertilizers were applied to the soils until 2014. Then, their application increased up to 12–17 t/ha per year. As for mineral fertilizers, their maximum amounts (on average, 150 kg of the active substance per hectare each year) were applied in 1982–1993; then, the rate of application decreased to 50–100 kg/ha per year. At the time of the field research, the arable lands on both sides of the studied shelterbelt belonged to different farms specializing in growing row and grain crops.

The oak stand has a high quality; its trees are well developed, inside the oak stand, young tree growth and shrub undergrowth can be seen as the features of a normally developing forest biocenosis. The amount of young trees in the undergrowth significantly increases along the margins of the shelterbelt in comparison with its central part; the coverage of the soil surface with herbs also increases in the marginal zone. This may be due to differences in surface lighting conditions between the central and marginal parts of the shelterbelt; these zones differ in the environmental conditions of plant growth.

Arable soils adjacent to the shelterbelt on both sides are medium-deep light clayey leached chernozems (Luvic Chernozems (Loamic, Aric, Pachic)) developed from calcareous loesslike heavy loam with the physical clay (<0.01 mm) content of about 50–60%. Under the shelterbelt, chernozems are stronger affected by burrowing animals (mole rats). According to the depth of effervescence, they were classified as medium-deep light clayey typical chernozems (Haplic Chernozems (Loamic, Aric, Pachic)) developed from calcareous loesslike heavy loam.

The morphological studies of soils were performed in several deep soil pits, two of which were in the center of the shelterbelt and three pits were on each side of the shelterbelt at distances of 10, 30, and 60 m from its edges. Morphological descriptions of soil profiles were supplemented by drawings of visually determined inclusions along the paths of burrowing animals on the front walls of pits for further calculation of the area occupied by krotovinas. Soil samples were taken from opposite lateral walls of the pit with subsequent averaging of samples. Layer-by-layer sampling was carried out to a depth of 180 cm (bottom of the pits); in deeper layers (to a depth of 4 m), auger samples were taken from two boreholes in each pit; then, these samples were also averaged. Soil samples for bulk density determination were taken with steel cutting rings of standard volume in triplicate.

In addition to studying the soils in pits, we studied the topsoil (0–20 cm) layer along three transects laid perpendicular to the shelterbelt and spaced apart at 10 m from one another. These transects crossed the shelterbelt and the arable land from its two sides to a distance of 100 m from the edges of the shelterbelt. Soil sampling along the transects was performed every 10 m on the arable land and every 6 m under the shelterbelt. In total, 30 samples were taken for the laboratory analysis from each field to the west and east of the shelterbelt, and 15 samples were taken under the shelterbelt (overall, 75 samples). At each sampling point, two duplicate samples (150 samples in total) were taken to determine the bulk density using steel rings of standard volume. Each sample consisted of two core samples taken from the upper and lower parts of the studied layer (0–20 cm).

The laboratory analyses included determination of particle-size distribution according to Kachinskii's method (GOST (State Standard) 12536), the organic carbon content according to Tyurin's (wet combustion) method (GOST 26213–91), the content of easily hydrolyzable nitrogen (GOST 26212–91), available

Table 1. Statistical parameters of the distributions of bulk density values and stocks of clay and Corg in the studied soils

Site	*n*	*Lim*	$X \pm \delta_X$	δ	*V*, %
Bulk density, g/cm^3					
West arable land	30	1.0–1.23	1.16 ± 0.01	0.053	4.6
East arable land	30	1.07–1.29	1.20 ± 0.01	0.044	3.7
Shelterbelt	15	0.84–1.22	1.02 ± 0.03	0.106	10.4
Clay stocks, t/ha					
West arable land	30	769–1029	904 ± 10	53	5.9
East arable land	30	639–1128	854 ± 17	92	10.8
Shelterbelt	15	471–686	605 ± 25	96	15.9
C_{org} stocks, t/ha					
West arable land	30	51.0–65.15	58.44 ± 0.71	3.87	6.6
East arable land	30	56.77–71.98	64.89 ± 0.74	4.08	6.3
Shelterbelt	15	50.90–87.08	69.17 ± 2.7	10.46	15.1

forms of phosphorus and potassium according to Chirikov's method (GOST 2620–91), the composition of the soil water extract (the contents of CO_3, HCO_3, Cl, SO_4, Ca, Mg, Na, and K ions) (GOST 26424–85, GOST 26425–85, GOST 26426–85, GOST 26427–85, GOST 26428– 85). The CO_2 of carbonates was determined by the acidimetric method. Statistical treatment of the obtained data was performed using Statistica software package.

Graphical interpretation of the results was carried out in different ways: as isolines of the lateral or radial (vertical) distribution of studied parameters (Fig. 1), graphs of the spatial distribution of average values of parameters from the center of the shelterbelt to the arable land (Figs. 2a and 2b), graphs of spatial changes of the parameters along the transects (Figs. 2c–2e), polygons of the statistical distribution of parameters (Fig. 3), and diagrams (Fig. 4).

RESULTS AND DISCUSSION

The most general morphometric parameters of the studied soils were found. Under the shelterbelt, the total thickness of A1, A1B, and BA1 horizons (thickness of humus profiles) averaged 76 cm, and the depth of effervescence averaged 78 cm. In the arable soils, these values constituted 68 and 84 cm, respectively. Thus, chernozems under the shelterbelt are characterized by thicker humus profiles and shallower depth of effervescence in comparison with the arable soils.

According to the analysis of average values of bulk density in the topsoil (0–20 cm), the differences between the three compared plots (arable land to the west and east of the shelterbelt and under the shelterbelt) are significant. The minimum bulk density (1.02 g/cm^3) is under the shelterbelt; the bulk density of the arable soils reaches 1.16–1.20 g/cm^3 (Table 1) with the maximum value (1.20 g/cm^3) to the east of the shelterbelt, on the field occupied by corn in the period of our studies (the field to the west of the shelterbelt was under winter wheat).

Considering the differences in the average bulk density under the shelterbelt (1.02 g/cm^3) and in the arable soil (1.18 g/cm^3), we determined that the mass of the upper layer of 0–20 cm of the soil under the shelterbelt is 86.4% of the mass of the identical soil layer on the arable field. The average stocks of clay fraction (<0.001 mm) and carbon of the soil organic matter in the arable soil were multiplied by a factor of 0.864 for the correct comparison of soil properties under the shelterbelt and on the arable field.

Figure 1 shows distribution of soil properties in the soil profiles under the shelterbelt and to the west and east of it. It can be seen that this distribution, including bulk density values (Fig. 1a) tends to be symmetric relative the central (axial) part of the shelterbelt. In our opinion, the indicated distribution of properties is genetically related to the functioning of the shelterbelt and to changes in the soils over the entire period of the shelterbelt existence. In particular, there could be similar trends in the formation of microclimatic conditions of soil formation. Thus, the zones of low bulk densities in the profiles of chernozems located at a distance of 30 m from the edges of the shelterbelt are of interest. Calculation of the area of krotovinas produced by mole rats in the studied profiles (Table 2) indicates that maximum loosening of soils by mole rats is observed in the soil profiles located at a distance of 30 m to the east and west of the shelterbelt. Additional research is necessary to identify the exact causes of this phenomenon. We can suppose that optimal moisture conditions for mole rats are formed in these zones; the shadowing effect of the shelterbelt of certain duration may also be important.

Under the shelterbelt, the bulk density in the entire soil profile (to a depth of 180–200 cm) is significantly

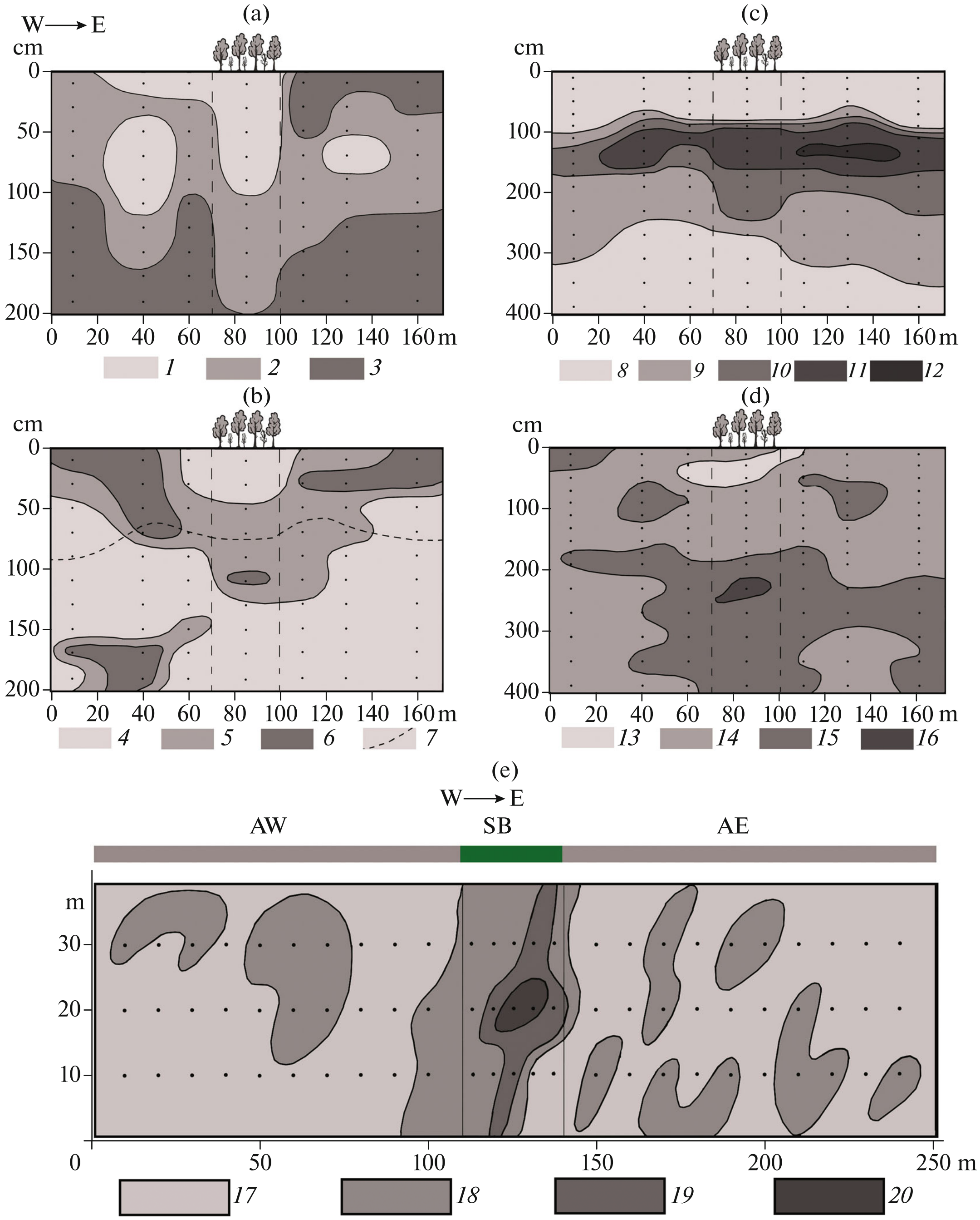

Fig. 1. Distribution of soil parameters under the shelterbelt and on the adjacent arable fields: (a) bulk density, g/cm^3 (*1,* <1.2; *2,* 1.2–1.4; *3,* > 1.4); (b) total content of clay and fine silt (<0.005 mm) fractions, % (*4,* <50; *5,* 50–54; *6,* > 54; symbol *7* denotes the depth of effervescence); (c) CO_2 of carbonates, % (*8,* <1; *9,* 1–3; *10,* 3–5; *11,* 5–7; *12,* >7); (d) exchangeable sodium, cmol(+)/kg (*13,* <0.16; *14,* 0.16–0.24; *15,* 0.24–0.28; *16,* > 0.28); (e) sand fraction (> 0.05 mm) in the topsoil (0–20 cm), % (*17,* <4; *18,* 4–6; *19,* 6–8; and *20,* > 8). Sampling sites are indicated by dots; AW—arable land to the west of the shelterbelt, SB—the shelterbelt, AE—arable land to the east of the shelterbelt. In figures 1a–1d, the vertical distribution of sampling points corresponds to the location and depth of soil sampling in the soil pits; for the center of the shelterbelt, averaged data on two soil pits are shown.

lower than that in the arable soils. The probable loosening impact of tree roots may extend to a depth of more than 2.5 m (tree roots were found in core samples from these depths). The activity of soil animals can also be the factor of soil loosening. In particular, the analysis of soil loosening by mole rats showed a large proportion of the loosened area (krotovinas) on front walls of the soil pits under the shelterbelt. As krotovinas produced by mole rats persist for a long time in the soil profiles, it can be assumed that there was a period of increased activity of these animals in the soil under the shelterbelt immediately after its planting.

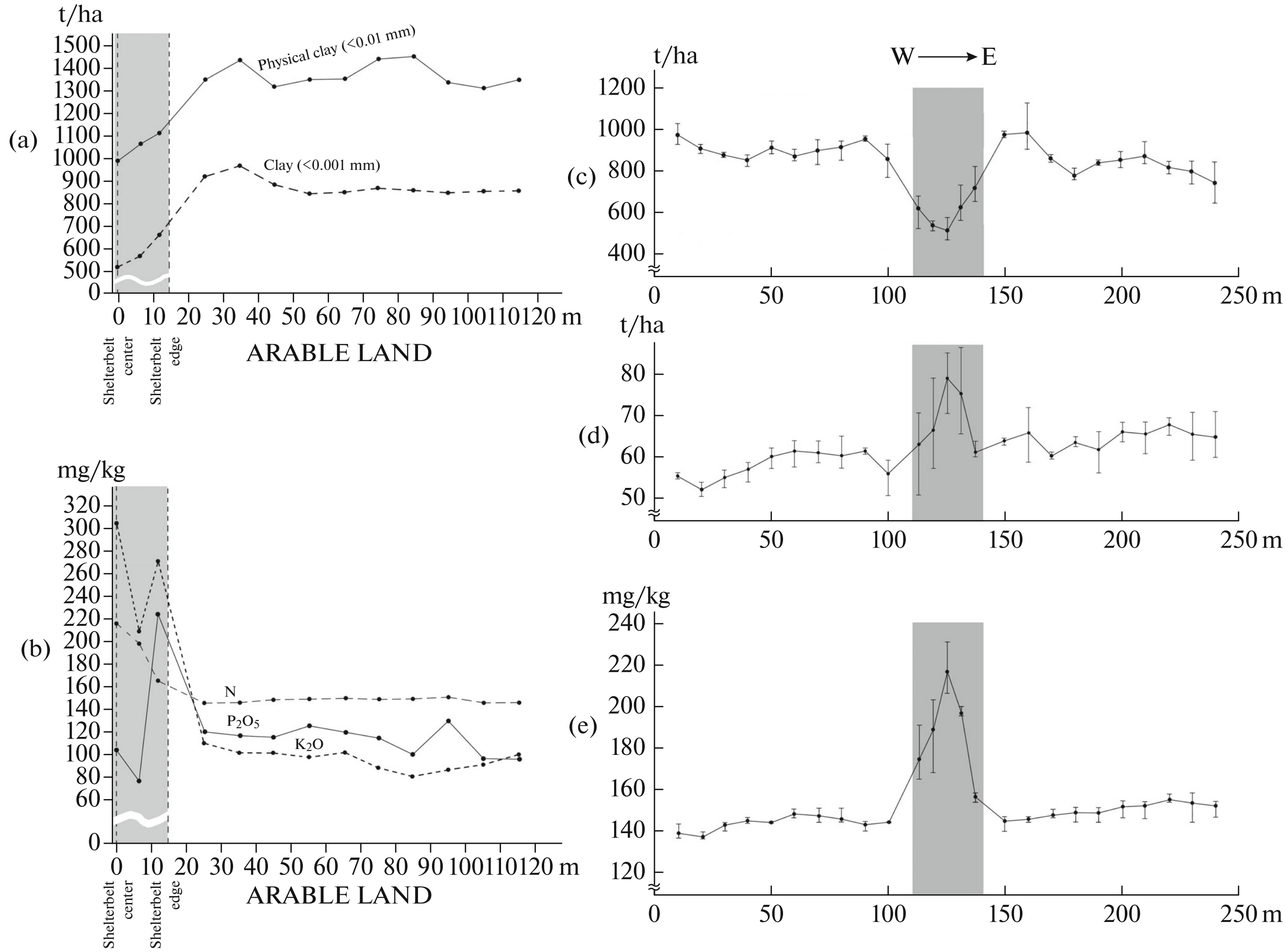

Fig. 2. (a) Average stocks of physical clay (<0.01 mm) and clay (<0.001 mm); (b) average contents of hydrolyzable nitrogen and available phosphorus and potassium in the topsoil (0–20 cm) layer in the soils of the shelterbelt and adjacent arable fields; and spatial distribution of (c) clay stocks, (d) C_{org} stocks, and (e) content of hydrolyzable nitrogen in the topsoil (0–20 cm) layer along the studied profiles. The zone of the shelterbelt is marked in gray color. In Figs. 2a and 2b, each point, except for the point in the center of the shelterbelt, is characterized by the average from six measurements; the point is the center of the shelterbelt is characterized by the average from three measurements. In Figs. 2c–2e, each point is characterized by data from three measurements.

This could happen in the first years after planting young trees, when the site could still function as a fallow overgrown with grasses, which could attract burrowing animals. This hypothesis is consistent with the results obtained by A.L. Aleksandrovskii in the Kulikovo field area [2]. It was found that the soil digging by mole rats in the medieval period gained maximum at the edges of old arable fields, near the grassy uncultivated land strips marking the boundaries between fields.

Table 2. Distribution of krotovinas produced by mole rats in the studied soils, % the section area

Layer, cm	Soils			
	shelterbelt, $n = 2$	arable land, 10 m from the edge, $n = 2$	arable land, 30 m from the edge, $n = 2$	arable land, 60 m from the edge, $n = 2$
0–40	10.0	0.3	3.6	0.8
40–80	66.4	44.2	50.8	50.1
80–120	46.6	35.4	57.5	36.3
120–160	18.7	7.2	23.7	10.5
0–160	35.4	21.8	33.9	24.4

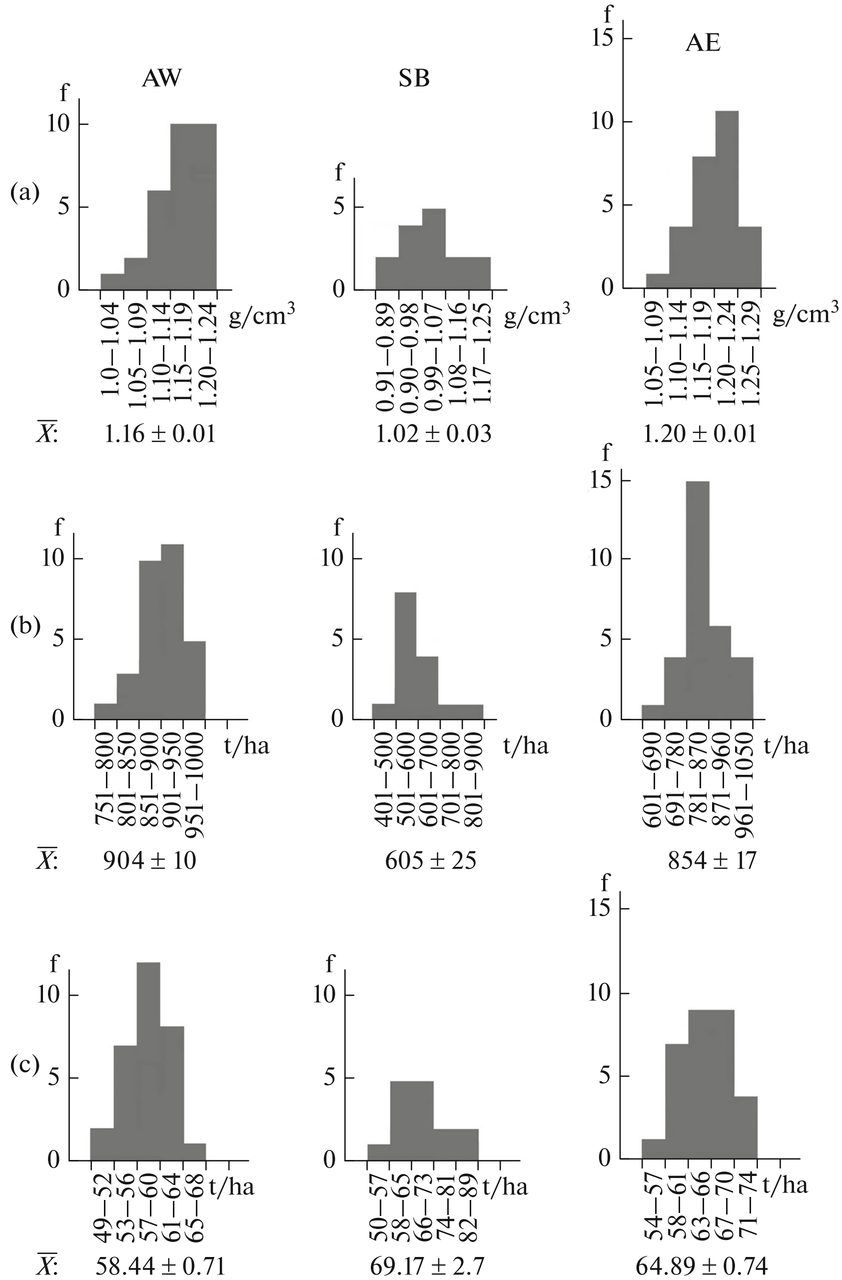

Fig. 3. Histograms of the distribution of (a) bulk density, (b) clay (<0.001 mm) stocks, and (c) C_{org} stocks in the topsoil (0–20 cm) layer of studied sites: (AW) arable land west of the shelterbelt (n = 30), (SB) shelterbelt (n = 15), and (AE) arable land east of the shelterbelt (n = 30).

Relatively small depth of effervescence at a distance of 30 m to the east and west of the shelterbelt and the well-shaped carbonate-illuvial horizons with a relatively high content of carbonates in these places (Fig. 1c) are probably due to the specificity of the migration of carbonates in the soils strongly affected by mole rats. A tendency for the accumulation of exchangeable sodium in a layer of 60–120 cm at the same locations is obvious (Fig. 1d), and this feature also reflects specificity of the soil climatic regimes favoring the rise of deep sodium-containing soil solutions and their lateral migration.

A somewhat coarser texture of the upper soil layers under the shelterbelt (Fig. 1b) can be interpreted as a result of the removal of fine particles into the underlying layers (lessivage), which is one of the most important elementary soil-forming processes in soils under broadleaved forests [3]. Spatial distribution of particle-size fractions capable of lessivage, i.e., clay (<0.001 mm) and fine silt (<0.005 mm) [18],

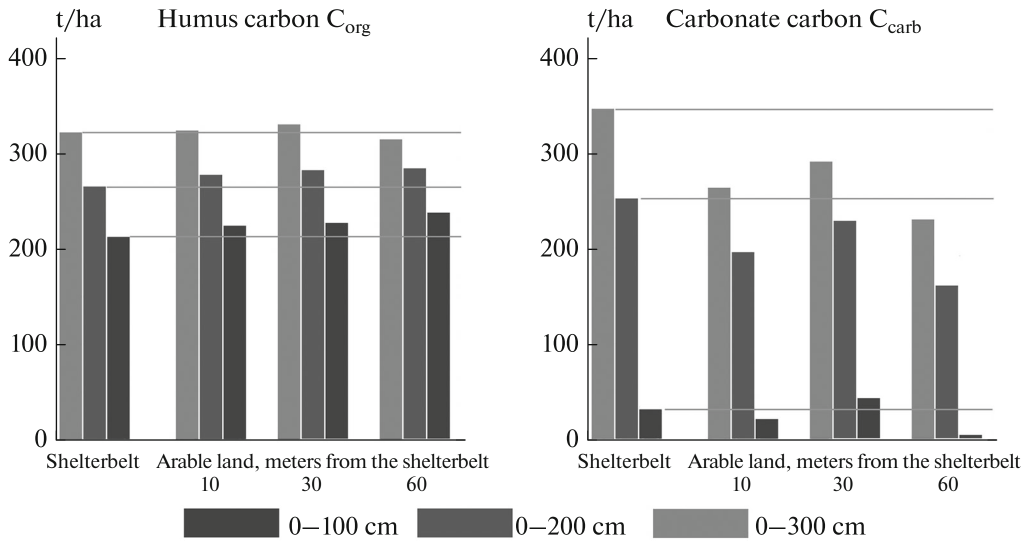

Fig. 4. Stocks of C_{org} and C_{carb} in the layers of 0–100, 0–200, and 0–300 cm of the studied soils.

indicates that the upper layer of 50–55 cm in thickness is depleted of these fractions (<50% of the mineral mass), whereas the layer of 50 (55)–130 cm is enriched in clay and fine silt.

The coefficient of textural differentiation (i.e., the ratio of the content of particles <0.005 mm in the BC horizon (54.2%) to their content in the A1B horizon (45%) in soils under the shelterbelt is 1.2. Differentiation of the soil profile according to the distribution of the fraction <0.005 mm was not detected in soils at a distance of 60 m from the edges of the shelterbelt. In the soil profiles at distances of 30 and 10 m from the shelterbelt, a tendency for the eluvial–illuvial redistribution of particles <0.005 mm is clearly seen, and the coefficient of textural differentiation in these places varies from 1.05 to 1.14. According to Fig. 1b, the depth of the soil layer enriched in the fraction <0.005 mm (50–54% of the total mineral soil mass) increases from the arable soils located 60 m from the shelterbelt to the soils near the shelterbelt and under the shelterbelt. In our opinion, this fact confirms the detected regularity of increasing vertical migration of clay particles in the soils under the shelterbelt and near it. These sites receive additional moisture during the snowmelt season due to the increased snow retention under the shelterbelt and in the immediate vicinity. In addition, the shadow effect of the shelterbelt can reduce moisture loss on evaporation and, therefore, create better conditions for the precipitation penetration into the soil during the warm season.

The spatial differences in the contents and stocks of fine fractions are confirmed by the results of the study of topsoil (0–20 cm) samples under the shelterbelt and on the adjacent arable fields with a definite tendency for an increase in the contents of clay and physical clay particles from the center of the shelterbelt towards its margins and adjacent arable areas (Fig. 2a).

According to the calculations, the average clay stock (<0.001 mm) in the topsoil (0–20 cm) under the shelterbelt is 605 t/ha, whereas the average value obtained for the both arable fields is 879 t/ha. The use of the correction factor for the differences in bulk density values (0.864) gives us the average clay stock in the arable topsoil equal to 879 × 0.864 = 759 t/ha. Thus, the difference between average clay stocks in the layer of 0–20 cm between the arable soil and the soil under the shelterbelt reaches 154 t/ha or 15.4 kg /m^2.

Stocks of physical clay (<0.01 mm) in the topsoil also tend to increase from the center of the shelterbelt towards the arable land; at distances >10 m from the edge of the shelterbelt, this parameter varies in the range of 1300–1450 t/ha (Fig. 2a). The stocks of clay (<0.001 mm) have a more complex spatial distribution increasing from the center of the shelterbelt to its edges and then in the arable soil at distances of up to 20 m from the shelterbelt; after that, there is a gradual decrease in this parameter. At distances of >50 m from the edge of the shelterbelt, clay stocks are nearly constant.

Taking into account the age of the shelterbelt (50 years), the average intensity of clay removal from the topsoil during the entire period of the shelterbelt growth is 3.1 kg/m^2 per decade. The development of lessivage under the shelterbelt is also confirmed by the following morphological observations. In the upper part of the soil profiles under the shelterbelt, some bleaching of the soil along the network of fissures takes place. In many places, the surface of the mineral soil under the litter layer consisting of leaves and branches has a light gray color owing to the accumulation of skeletans, especially in the areas of microelevations near tree trunks.

Taking into account the removal of finest particles from the topsoil under the shelterbelt, we may expect the relative accumulation of coarse particles, primarily sand fraction, in the soils under the shelterbelt. Indeed, such a regularity is seen from the results of particle-size distribution analysis (Fig. 1e).

The average C_{org} stock in the topsoil (0–20 cm) layer under the shelterbelt ($n = 15$) is 69 t/ha; in topsoil of the adjacent arable land ($n = 60$), it equals 62 t/ha. The real stock of C_{org} in the arable topsoil (corrected for the differences in the topsoil mass) is $62 \times 0.864 = 54$ t/ha.

When studying spatial differences in the topsoil bulk density and stocks of clay and organic carbon, a decrease in the coefficients of their variation in the direction from the shelterbelt to the arable fields can be expected because of some leveling of the properties of regularly tilled soils. Under the shelterbelt, the conditions of soil formation can be determined by differences in microclimatic conditions created by forest vegetation in the center of the shelterbelt and in its peripheral part.

The revealed significant differences in the bulk density and clay and organic carbon stocks in chernozems under the shelterbelt and on the adjacent arable fields are supplemented by data on the statistical parameters of their distribution. In our opinion, they reflect certain tendencies in the development of soil-forming processes over time (Fig. 3).

On arable lands to the west and east of the shelterbelt (indicated in Fig. 3 as AW and AE, respectively), histograms of the distribution of bulk density in the topsoil (0–20 cm) show an increase in the frequency of occurrence of this parameter in the region of higher values compared to the median, i.e., the right-side asymmetry of the parameter distribution is observed (Fig. 3a). This attests to the development of compaction of arable soils over time. In the soil under the shelterbelt (Fig. 3a, SB), on the contrary, a tendency for the shift of the maximum occurrence frequency of this parameter to lower values in comparison with the median takes place, which suggests that forest vegetation has the loosening effect on soil and that this tendency is likely not to change in the coming years and decades.

In the soils of the shelterbelt, the left-side asymmetry of the distribution of clay stocks (an increase in the frequency of occurrence of this parameter in the region of lower values) attests to a directed depletion of clay from the topsoil, while the opposite trend is observed for the arable soils (Fig. 3b).

If the removal of clay from the topsoil under the shelterbelt can be explained by the relatively moist and cool microclimatic conditions, then the accumulation of the clay fraction in the upper layers of arable chernozems (Fig. 3b) and, especially, within 20-m-wide zones adjacent to the shelterbelt requires special consideration. According to the earlier suggested assumption [28], an increase in the content of clay (and physical clay) fractions in the Ap horizon of forest-steppe chernozems may be due to the physical comminution of soil during plowing with an increase in the content of soil microaggregates and clay fraction. The probability of more frequent passages of agricultural machinery along the boundaries of arable fields (in our case, near the shelterbelt) should also be taken into account, as it explains the maximum contents of clay and physical clay fractions in the plow layer of arable soils near (about 20 m) the shelterbelt.

The distribution of C_{org} stocks reflects the tendency for the right-side asymmetry of this parameter in the arable soils and its left-side asymmetry in the soils under the shelterbelt (Fig. 3c). This occurs despite the fact that the stocks of organic matter in the soils of the shelterbelt are significantly higher than those in the arable soils. Previous studies showed that in the first decades (50–70 years) of growth of the shelterbelts, the organic matter accumulates in soils under shelterbelts of agroforest landscapes both in the Central Russian Upland and on the Great Plains of the United States [26, 27]. According to detailed information of American researchers on Mollisols of Iowa, the peak of humus accumulation in the topsoil horizons under the shelterbelts is observed in about 30 years of their growth; later, the intensity of this process decreases [34]. Therefore, the found tendency for an increase in the humus content of chernozems under the shelterbelts in the first decades of their growth can reflect the particular stage of the soil evolution; later, it may be replaced by the opposite tendency for a decrease in the humus stocks and degradation of the humus state of former steppe soils under forest vegetation. The left-side asymmetry of the curve of distribution of C_{org} stocks under the shelterbelt (Fig. 3c, SB) may be indicative of such a transition in the stages of soil development.

The distribution of organic and inorganic carbon in the entire profiles of studied soils was analyzed on basis of calculated layer-by-layer carbon stocks in the soil profiles to a depth of 3 m (Table 3, Fig. 4). A comparison of averaged values indicates that the stock of organic carbon in the soil under the central part of the shelterbelt is higher than that in the arable soils 10 and 30 m away from the shelterbelt edge only in the upper (0–20 cm) layer. In the layer of 20–60 cm, the opposite tendency is observed, i.e., the average stock of organic carbon under the shelterbelt is lower (on average by 19 t/ha) than in the soils of adjacent arable sites, especially noticeable differences were found for the layer of 20–40 cm. In deeper layers, the differences were insignificant. It can be assumed that favorable conditions for humus accumulation formed in the layer of 20–60 cm of the arable soil in the zone of influence of the shelterbelt. In particular, these soils are subjected to additional input of organic substances in the form of leaves and branches carried by wind

Table 3. Stocks of carbon in the studied soils (according to the average values for paired soil profiles)

Layer, cm	Carbon stocks, t/ha							
	under the shelterbelt		10 m from edges of the shelterbelt		30 m from edges of the shelterbelt		60 m from edges of the shelterbelt	
	C_{org}	C_{carb}	C_{org}	C_{carb}	C_{org}	C_{carb}	C_{org}	C_{carb}
0–20	71.19	0	66.40	0	64.24	0	74.71	0
20–40	50.04	0	62.65	0	60.94	0	66.56	0
40–60	40.96	0	45.17	0	48.47	2.66	45.21	0
60–80	30.26	1.82	31.75	0	32.27	12.35	31.06	0
80–100	24.17	29.40	20.20	23.12	24.36	30.17	22.48	2.97
100–120	15.63	37.87	15.17	40.36	18.17	40.57	13.23	27.65
120–140	11.81	40.83	11.10	42.54	8.07	50.23	9.30	39.71
140–160	7.99	39.09	9.96	36.99	6.51	42.99	7.34	35.09
160–180	6.12	32.64	7.62	29.87	9.05	29.94	6.03	33.43
180–200	9.03	24.75	9.17	26.14	11.35	23.81	8.46	23.54
200–220	9.51	24.07	9.39	22.19	10.93	18.71	7.79	18.23
220–240	9.99	23.38	9.61	18.24	10.50	13.61	7.11	12.92
240–260	11.33	19.39	8.65	10.82	9.85	10.82	6.46	13.58
260–280	12.67	15.40	7.67	9.12	9.19	8.03	5.81	14.24
280–300	10.07	10.01	8.68	8.14	8.63	7.50	5.99	12.11

from the shelterbelt to the adjacent arable field. Periodically dying parts of tree root systems, including thin roots extending to a distance >10 m from the edge of the shelterbelt, can also be an additional source of humus. Fine (1–6 mm) oak roots concentrated mainly in the layer of 30–60 cm were identified in an appreciable amount in the soil pits on the arable fields near the shelterbelt.

The relative accumulation of humus in the layer of 20–60 cm of the arable soil (as compared with the soil under the shelterbelt) may be explained by the intraprofile migration of humic substances under relatively cool microclimatic conditions established under the influence of the shelterbelt.

However, a different explanation—the beginning of dehumification of chernozems under forest vegetation in the layer of 20–60 cm—can also be suggested. Additional studies are needed for the final conclusions on this issue.

The analysis of the layer-by-layer distribution of the carbon stocks in the 1-, 2-, and 3-m-deep layers of the studied soils (Fig. 4) shows that differences in the organic matter content are clearly seen in the upper soil meter and become leveled when considering the stocks of organic carbon in the 3-m-deep soil profiles.

There is an evident tendency for leaching of carbonates from the arable soils in comparison with the soils under the shelterbelt. Thus, in the arable soil at a distance of 10 m from the shelterbelt, the stock of carbonate carbon in the 3-m-thick soil layer is about 100 t/ha lower than that under the shelterbelt; at a distance of 60 m, it decreases by additional 30 t/ha. There is a slight increase in the stock of carbonate carbon in the arable soils located 30 m away from the edge of the shelterbelt in comparison with the arable soils located closer to the shelterbelt and farther from it. However, even in this place, the stocks of carbonate carbon in the 2- and 3-m-deep soil layers are smaller than those in the soils under the shelterbelt. The activation of carbonate accumulation at a distance of 30 m from the edge of the shelterbelt was previously discussed in the context of the microclimatic conditions and an increase in the intensity of soil digging by burrowing animals.

The average loss of carbonate carbon from the arable soils was estimated at 57 t/ha for the layer of 0–200 cm and 84 t/ha for the layer of 0–300 cm. The reasons for the enhanced leaching of carbonates from the profiles of arable chernozems are as follows. Water transpiration by plants on the arable land ends after harvesting in the late summer or early autumn, which leads to a greater soil wetting by atmospheric precipitation and the leaching of carbonates. This fact is in agreement with the concept of humidization of the water regime of arable chernozems [8]. In the soil under the shelterbelt, water uptake by the roots and further transpiration continues in the later summer and early autumn. Therefore, better conditions for the conservation of

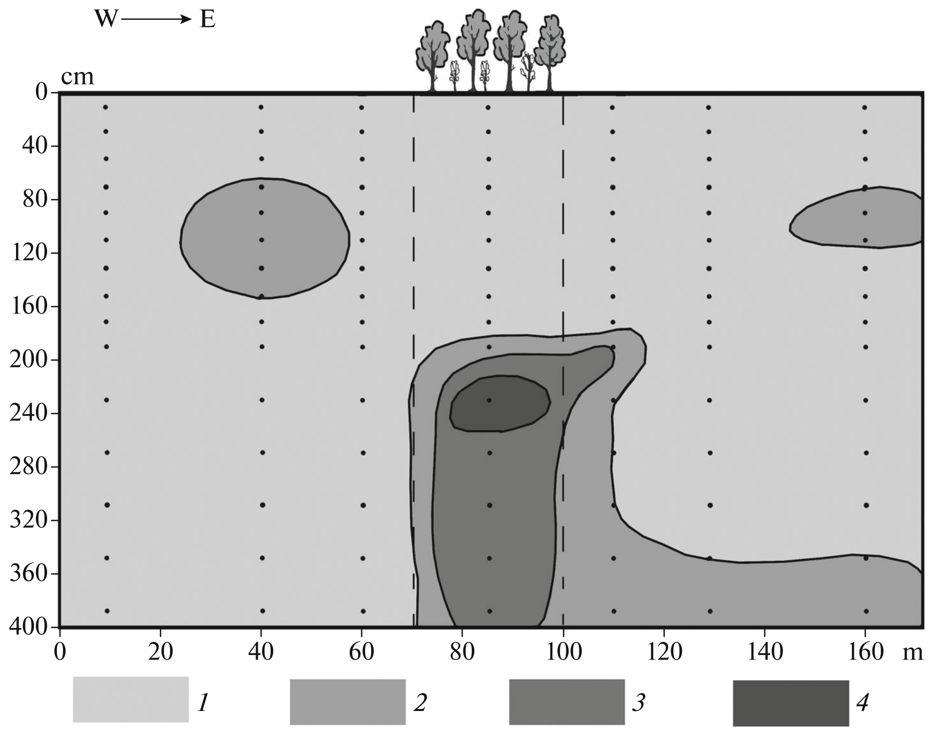

Fig. 5. Distribution of sodium concentrations in the soil water extracts in the area affected by the shelterbelt, cmol(+)/kg: (*1*) <0.06, (*2*) 0.06–0.08, (*3*) 0.08–0.1, and (*4*) > 0.1.

soil carbonates exist in this soil in comparison with soils on the adjacent arable fields.

There were no obvious regularities in the spatial distribution of hydrolyzable nitrogen and available phosphorus and potassium in the arable soils (Fig. 2b). At the same time, the distinct maxima in the contents of these compounds were in the soils under the shelterbelt, which may be explained by their natural accumulation in the upper soil layers. In the arable soils, the contents of these compounds are largely controlled by the application of nitrogen, phosphorus, and potassium mineral fertilizers and by the removal of these nutrients with harvested crops.

A noticeable increase in the content of available phosphorus and potassium in the soils under the shelterbelt is mainly observed in its marginal parts closer to the border with the arable land. We suppose that this is the result of the movement of these nutrients from the arable land, which regularly receives mineral fertilizers, to the periphery of the shelterbelt. These nutrients are taken up by tree roots from the arable soil near the shelterbelt and then return to the soil with the litter of leaves and branches. This describes the functioning of shelterbelts as biogeochemical barriers, which accumulate the agricultural chemicals, including phosphorus and potassium, in the upper soil layer along their periphery.

The distribution patterns of the stocks of clay, organic carbon, and hydrolyzable nitrogen are clearly differentiated in the soils under the shelterbelt (Figs. 3c–3e). These three indicators were chosen as examples of pronounced spatial differentiation of soil properties from the center of the shelterbelt to its edges. This differentiation is a result of different intensities of soil-forming processes in different parts of the shelterbelt. Earlier, American researchers called attention to such regular changes in the soil properties [33].

In our opinion, the minimum stocks of clay in the upper soil layer in the central part of the studied shelterbelt are the result of more intensive water infiltration under the most shaded part of the shelterbelt with well-developed tree crowns. Here, the maximum stocks of soil organic matter and hydrolyzable nitrogen are observed; they are indicative of the active humification of plant residues. This is probably due to the specific features of the microclimate and favorable hydrological regime of the soils.

The analysis of the salt regime of soils associated with the shelterbelts is of theoretical and applied interest. For example, studies of water extracts from soils under old–age shelterbelts of the Kamennaya Steppe revealed an increase in the concentration of salts directly under the tree stands, especially in the central (axial) parts of wide shelterbelts [24, 25].

Our study of the composition of water extracts from the soils of the shelterbelt and arable fields did not indicate obvious features of salt accumulation under the shelterbelt.

The total content of dissolved salts in soil samples taken to a depth of 4 m under the shelterbelt and on the adjacent arable fields did not exceed 0.2% (2 g/L) and in most samples was within 0.05–0.1% (0.5–1 g/L). At the same time, a weak tendency for the rise in the concentration of soluble salts in soils under the shelterbelt was found. In deep (>2 m) soil layers in the central part of the shelterbelt, the concentration of magnesium ions (0.3–0.45 cmol(+)/kg) was definitely higher than that at the same depth in the arable soils (0.1–0.3 cmol(+)/kg). A tendency for sodium accumulation was also found at the same depths under the shelterbelt (Fig. 5). With an increase in the age of the tree stand and in the degree of development of the root system of oak trees, the tendency for the accumulation of salts in the soils under the shelterbelt will probably increase.

CONCLUSIONS

Forest shelterbelts are characterized by their own structural organization and specific development over time. The shelterbelts influence the direction and intensity of the soil-forming processes both under them and on the adjacent arable land.

(1) Oak shelterbelts oriented in the meridional direction on flat interfluves in the forest-steppe zone with medium-deep chernozems on heavy carbonate loesslike loams have led to the formation of spatial differences in soils under the shelterbelts and on the adjacent arable land in about 50 years of their growth. Regular changes in soil properties have been identified by statistical distribution of parameters, their spatial trends along the transects, and by isolinear interpretation of the lateral and radial distribution of soil properties relatively the center of the shelterbelt to the west and east of it.

(2) The soils under the oak shelterbelts significantly differ from the soils of the adjacent arable land in a bulk density, lower stocks of clay (<0.001 mm) and physical clay (<0.01 mm), and larger stocks of organic matter in the topsoil (0–20 cm) layer.

(3) Judging from the asymmetry of statistical distribution curves of the studied soil parameters, the processes of soil compaction on the arable land near the shelterbelt tend to be further developed, while the further loosening of the upper soil layers is predicted in the soil under the shelterbelt. Similarly, further trends in the development of the removal of clay from the topsoil layer and a decrease in the intensity of humus accumulation in soils under the shelterbelt are justified.

(4) The long-term growth of the oak shelterbelt influences the morphology of the profile of chernozems. During the first years after planting young trees, when the site continued to be a grass-sodded land, the chernozem of the shelterbelt was under noticeable activity by mole rats. This was reflected in the increase in the area occupied by the animal tracks, especially in the layer of 0–80 cm. In the modern soils of the shelterbelt, the bulk density is markedly reduced to a depth of 180–200 cm in comparison with that in the surrounding arable soils. On the arable fields 30 meters to the west and east from the shelterbelt edges, the areas of decreased bulk density are also formed. This corresponds to the zones of maximum soil digging by mole rats, which is explained by the specificity of the microclimatic conditions of soil formation at these sites. These sites are also characterized by a shallower depth of effervescence and well-shaped carbonate-illuvial horizons with a relatively high content of carbonates. A tendency for the accumulation of exchangeable sodium in the layer of 60–120 cm in these soils also reflects the specificity of soil climatic regimes favoring the ascending migration of deep sodium-containing soil solutions. In the soils under the shelterbelt, the process of textural differentiation of the profile takes place as judged from the content and stocks of clay (<0.001 mm) and fine silt (<0.005 mm). The removal of these fractions is observed in the upper 50-cm-thick layer, and their accumulation occurs in the layer of 50–130 cm. In 50 years of growth of the shelterbelt, the coefficient of textural differentiation of the profile has increased to 1.2 in comparison with 1.0 in the arable soil before planting the shelterbelt. The arable soils adjacent to the shelterbelt contain less carbonates than the soils under the shelterbelt; the amount of removed carbonates averages 57 t/ha for the layer of 0–200 cm and 84 t/ha for the layer of 0–300 cm. In the soils under the shelterbelt, the initial stage of accumulation of soluble salts has been detected according to the concentration of sodium and magnesium ions in the water extracts from the soil in the layer of 200–400 cm.

(5) Within the shelterbelt, the soil properties also display certain spatial differentiation along the cross-section. The maximum rates of the removal of clay and the accumulation of C_{org} and hydrolyzable nitrogen are revealed in the center of the shelterbelt, whereas the maximum contents of available phosphorus and potassium in the topsoil are characteristic of the soils in the marginal parts of the shelterbelt.

(6) The influence of the studied shelterbelt on the soil properties of adjacent arable fields can be traced to a distance of 50–60 m from its edges. Obvious differences in quantitative parameters are noted for clay stocks in the topsoil (0–20 cm) layer. For some other indicators (stocks of C_{org} and the contents of hydrolyzable nitrogen and available phosphorus and potassium in the Ap horizon), no definite spatial trends have been established for arable soils near the shelterbelt.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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