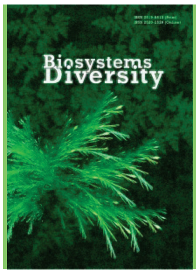

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The influence of forest vegetation on the physical properties of chernozems in the steppe zone of Ukraine

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Targeted changes in the physical properties of soils, including through afforestation, are an important component of land use practices that are aimed at obtaining sustainable crop yields, which is especially important for potentially highly fertile chernozem soils. The physical properties of ordinary chernozems under steppe vegetation (used as a control) and plantings of *Robinia pseudoacacia* L. and *Quercus robur* L., as well as chernozem luvosol under natural forest vegetation, were studied in the field, as well as in laboratory conditions using soil samples taken from 12 areas established within Dnipropetrovsk region (Ukraine). As a result of the study, it was established that the studied ordinary chernozems and luvic chernozems are classified as silty loam according to their granulometric composition. The growth of acacia and oak plantations led to an increase in sand content and a decrease in silt content, and the growth of natural forest vegetation contributed to an increase in sand and silt content and a decrease in clay content in black soils. The influence of forest vegetation on chernozems led in the 0–20 cm layer to an increase in the content of aggregates of fractions > 2 mm and water-resistant aggregates of fractions > 0.5 mm and a decrease in the content of aggregates of fractions < 1 mm and water-resistant aggregates of fractions < 0.5 mm compared to chernozems under steppe vegetation. The growth of forest vegetation caused a decrease in the density and density of the solid phase, and an increase in the total porosity of chernozems in the layers of 0–20 and 20–40 cm. The influence of forest vegetation on ordinary chernozems and luvic chernozems contributed to an increase in the content of available water for plants and an increase in their water permeability compared to ordinary chernozems under steppe vegetation. Ordinary chernozems under acacia and oak plantations are characterized by increased electrical resistivity, and luvic chernozems under natural forest vegetation are characterized by reduced electrical resistivity compared to ordinary chernozems under steppe vegetation. The growth of forest vegetation contributed to a decrease in the dielectric constant of chernozems. The influence of natural forest vegetation leads to more pronounced changes in the physical properties of chernozems compared to the influence of acacia and oak plantings.

Keywords: granulometric composition; density; available water for plants; ordinary chernozems; oak plantings; forest vegetation.

Introduction

Studying the possibilities of managing the properties and regimes of chernozems, which ensure food security in many countries of the world, is an important issue that needs to be addressed.

The discussion about the formation of chernozem soils under forest vegetation in steppe conditions has been ongoing for a long time (Travleev, 1996; Dudek et al., 2022). Comprehensive studies of soils, the genesis of which is associated with artificial and natural forest vegetation in the steppe zone of Ukraine, confirm the formation in these conditions of chernozem soils, the properties of which differ to a certain extent from the properties of zonal chernozems that formed under steppe vegetation (Belova & Travleev, 1999).

Studies of chernozem soils in Europe carried out in recent years also confirm the increased interest of scientists in the peculiarities of the genesis of chernozems under forest vegetation. Eckmeier et al. (2007) note that the assumption that modern Central European chernozems are relicts of steppe soils contradicts paleobotanical data of early reforestation, as well as soil studies that date the formation of chernozems to the Early Holocene, which indicates the possibility of the formation of chernozems under woody vegetation. Vysloužilová et al. (2014) as a result of a study devoted to the plant aspect of soil formation in chernozems, it is noted that in Central Europe, chernozems are found in conditions where there are no climatic factors for the existence of the steppe. The researchers came to the conclusion that the high stability of soil organic matter determined the preservation of chernozems in areas dominated by forest vegetation. Labaz et al. (2018) note that unfavorable environmental conditions for the development of chernozems in Central Europe have raised the question of their origin and age, as well as the conditions necessary for the conservation of chernozems in Central Europe in a humid climate. As a result of the studies, it was found that the direction of transformation of native chernozems during the Holocene is closely related to their position in the landscape, which influenced the intensity of erosion/accumulation and drainage conditions (soil moisture regime).

Lasota et al. (2019) found that the formation of chernozems in Poland is associated with woody vegetation. In general, fresh and moist deposits of broad-leaved forests develop on chernozems, as well as fresh habitats of high-mountain broad-leaved forests, which are associated with multi-species broad-leaved forest stands. In the work of Łabaz et al. (2019) it is emphasized that in the forest belt of South-Western Poland, various chernozem soils with a thick mollic horizon, rich in humus, dark-colored, structural and saturated with base cations are relatively common. It is noted that most of these soils may have a similar initial (chernozem) history of a thick humus horizon associated with climatic conditions and vegetation of the late Pleistocene and Neolithic. However, these soils exist on different bedrocks and under different moisture conditions, which indicates the formation of chernozems not only in pronounced steppe conditions under zonal vegetation.

Labaz et al. (2022) note that even in a moderate humid climate, as in Southeastern Poland, mixed broad-leaved forests, consisting of tree species that acidify the soil, cannot quickly destroy black soils. The results of physicochemical and morphological transformations are weaker than soil destruction due to water erosion and justify controlled afforestation of relict chernozems and phaeozems as a means of preserving them from rapid destruction. This issue has important theoretical and practical significance, since artificial and natural forests often attract the interest of scientists from the point of view of their influence on soil conservation, changes in soil properties during the growth and development of forest vegetation (Han et al., 2021; Dong & Kou, 2022; Tian et al., 2023).

In recent years, the influence of artificial forest plantations of various species and ages on soils, including in steppe conditions, has been most actively studied (Dubyna et al., 2023). Xiang et al. (2023) note the positive effect of planting shrubs on air permeability, water retention and nitrogen fixation in the soil. However, the main factors that determined soil quality in this study were soil bulk density, porosity, capillary water holding capacity, soil organic carbon and total phosphorus. Research by Dong et al. (2022) revealed the greatest positive effect of shrub vegetation on the soil compared to meadow and forest vegetation, which was manifested in changes in the content of sand, silt and clay particles, soil organic matter, macroaggregates and microaggregates. Some studies note the negative impact of *Robinia pseudoacacia* L. plantings on soil properties, in particular, a significant moisture content and a decrease in clay content were found (Sytnyk et al., 2022; Wu et al., 2023). Su et al. (2022) note that the growth of *Quercus acutissima* plantings leads to a greater increase in the content of clay and silt in the upper soil horizons compared to *Robinia pseudoacacia* plantings. The growth of oak plantations also contributes to a decrease in soil density and an increase in soil porosity. The authors note that particle size distribution, with which density and porosity are correlated, can be used to assess the influence of vegetation on soils. The more pronounced positive effect of *Quercus robur* L. plantings compared to *Robinia pseudoacacia* L. plantings on Calcic chernozem is also confirmed by the results of our research (Gorban, 2021; Gorban et al., 2021; Gorban & Huslystyi, 2023).

Studies of the influence of natural forest vegetation on the properties of steppe soils are much less numerous compared to the influence of artificial forest vegetation. In the work of Zhang et al. (2022) it was noted that restoration of natural vegetation increases the sequestration of soil organic carbon and nitrogen by increasing the input of crop residues and reduces the decomposition of soil organic matter. Restoration of natural vegetation promotes better changes in soil properties compared with artificial vegetation (Wang et al., 2021). The soils of natural forests in the steppe zone of Ukraine are characterized by the highest quality of structure compared to soils of artificial plantings and zonal chernozems (Yakovenko et al., 2024).

An analysis of publications in recent years shows the predominance of interest in changes in soils under forest vegetation from the point of view of their chemical and physicochemical properties, while the results of studies of changes in the complex of physical properties of soils remain limited. Based on this, the goal of our work is to assess changes in the physical properties of soils under the influence of forest vegetation in the steppe zone of Ukraine.

Materials and methods

Study area. To study changes in the physical properties of chernozems under the influence of forest vegetation, 12 plots were established within Dnipropetrovsk region, which is located in the steppe zone of Ukraine (Fig. 1). Calcic Chernozem under steppe vegetation was used as a control and studied in the example of plots 1, 2 and 3.

Site 1 (48°45'36.9" N 35°27'40.5" E) was located within the virgin steppe land of a watershed plateau. Herbaceous vegetative cover was closed, consists of *Festuca valesiaca* Schleich. ex Gaudin, *Koeleria macrantha* (Ledeb.) Schult., *Thymus marschallinus* Wilid., *Linum hirsutum* L., *Salvia nemorosa* L., *Artemisia austriaca* Jacq. and other herbaceous plant species. Soil profile description: A1 (0–7 cm), A2 (7–26 cm), Bk1 (26–42 cm), Bk2 (42–57 cm), Ck (57–120 cm+). The soil is a Calcic Chernozem.

Site 2 (48°32'39" N 33°54'40" E) was located in an arable field that was bare at the time of sampling. Soil profile description: A1 (0–10 cm), A2 (10–23 cm), B (23–52 cm), Bk (52–81 cm), Ck (81–120 cm+). The soil is a Calcic Chernozem.

Site 3 (47°41'28" N 33°38'44" E) was located in an arable field that was bare at the time of sampling. Soil profile description: A1 (0–10 cm), A2 (10–23 cm), B1 (23–50 cm), B2 (50–77 cm), Ck (77–120 cm+). The soil is a Calcic Chernozem.

Calcic Chernozem under *R. pseudoacacia* plantations were studied on the example of plots 4, 5 and 6.

Site 4 (48°45'28" N 35°29'33" E) was laid on the watershed plateau. Forest stands were represented by *R. pseudoacacia* aged about 65 years. Average tree height was 4–6 m, stem diameter was 10–12 cm. Stand canopy density 0.7. *Elytrigia repens* L., *Poa angustifolia* L., *Chelidonium majus* L. predominate in the herbaceous cover. Soil profile description: A (0–14 cm), B (14–34 cm), Bk (34–56 cm), Ck (56–120 cm+). The soil is Calcic Chernozem.

Site 5 (48°31'53" N 33°54'07" E) was laid on the watershed plateau. Forest stands were represented by *R. pseudoacacia* aged about 55 years. Average tree height was 6–7 m, stem diameter was 14–16 cm. Stand canopy density 0.6–0.7. *Poa angustifolia* L., *Chelidonium majus* L., *Elytrigia repens* L., *Geum urbanum* L. predominate in the herbaceous cover. Soil profile description: A1 (0–10 cm), A2 (10–38 cm), B (38–57 cm), Bk (57–78 cm), Ck (78–120 cm+). The soil is Calcic Chernozem.

Site 6 (47°41'16" N 33°39'03" E) was laid on the watershed plateau. Forest stands were represented by *R. pseudoacacia* aged about 50 years. Average tree height was 7–8 m, stem diameter was 9–14 cm. Stand canopy density 0.6. *Poa angustifolia* L., *Elytrigia repens* L. predominate in the herbaceous cover. Soil profile description: A1 (0–10 cm), A2 (10–30 cm), B1 (30–50 cm), B2 (50–68 cm), Ck (68–120 cm+). The soil is Calcic Chernozem.

Calcic Chernozem under plantings of *Q. robur* were studied using the example of plots 7, 8 and 9.

Site 7 (48°45'27" N 35°30'10" E) was located on a watershed plateau. Forest stand was represented by *Quercus robur* L., aged about 65 years. Average tree height was 7–9 m, stem diameter 10–14 cm. Stand canopy density 0.9. Rows of oak trees was alternated with rows of shrubs: *Acer tataricum* L., rarely *Euonymus europaeus* L. In the herbaceous cover *Elytrigia repens* L., *Verbascum lychnitis* L., *Ajuga genevensis* L. predominate. Soil profile description: A1 (0–9 cm), A2 (9–42 cm), Bk1 (42–62 cm), Bk2 (62–81 cm), Ck (81–120 cm+). The soil is Calcic Chernozem.

Site 8 (48°31'52" N 33°54'30" E) was laid on a watershed plateau. Forest stand was represented by *Quercus robur* L., aged about 70 years. Average tree height was 12–14 m, stem diameter 22–24 cm. Stand canopy density 0.8. Rows of oak trees was alternated with rows of shrubs: *Acer tataricum* L. In the herbaceous cover *Elytrigia repens* L., *Salvia verticillata* L., *Ajuga genevensis* L. predominate. Soil profile description: A1 (0–12 cm), A2 (12–44 cm), B (44–65 cm), Bk (65–87 cm), Ck (87–120 cm+). The soil is Calcic Chernozem.

Site 9 (47°41'29" N 33°38'52" E) was laid on a watershed plateau. Forest stand was represented by *Quercus robur* L., aged about 50 years. Average tree height was 7–9 m, stem diameter 9–12 cm. Stand canopy density 0.7. In the herbaceous cover *Elytrigia repens* L. predominate. Soil profile description: A1 (0–10 cm), A2 (10–20 cm), B1 (20–45 cm), B2 (45–78 cm), Ck (78–120 cm+). The soil is Calcic Chernozem.

Luvic Chernozem under natural forest vegetation were studied using the example of plots 10, 11 and 12.

Site 10 (48°47'19" N 35°27'20" E) was located on the middle ravine slope (aspect N). Natural forest was primarily formed by *Quercus robur* L., *Acer platanoides* L., *Fraxinus excelsior* L., *Tilia cordata* Mill., with rather abundant *Ulmus minor* Mill. and *Euonymus verrucosa* Scop. Herbaceous cover was predominantly composed of *Stellaria holostea* L., *Galium aparine* L., *Glechoma hederacea* L., *Asarum europaeum* L., *Viola odorata* L., *Polygonatum multiflorum* (L.) All. Soil profile description: Ah1 (0–12 cm), Ah2 (12–33 cm), Ah3 (33–67 cm), Ah4 (67–96 cm), Bt (96–140 cm), Ck (140–166 cm+). The soil is a Luvic Chernozem.

Site 11 (48°10'49" N 35°08'28" E) was located on the middle ravine slope (aspect N). Natural forest was primarily formed by *Quercus robur* L., *Fraxinus excelsior* L. Herbaceous cover was predominantly composed of *Chelidonium majus* L., *Viola odorata* L., *Polygonatum multiflorum* (L.) All., *Chaerophyllum temulum* L., *Alliaria petiolate* (M.Bieb.) Cavara & Grande, *Galium aparine* L. Soil profile description: Ah1 (0–10 cm), Ah2 (10–30 cm), Ah3 (30–50 cm), Bt1 (50–100 cm), Bt2 (100–150 cm), Ck (150–170 cm+). The soil is a Luvic Chernozem.

Site 12 (48°10'50" N 35°08'28" E) was located on the middle ravine slope (aspect S). Natural forest was primarily formed by *Quercus robur* L., *Acer campestre* L. Herbaceous cover was predominantly composed of *Anthriscus sylvestris* (L.) Hoffm., *Polygonatum multiflorum* (L.) All., *Pulmonaria obscura* Dumort., *Viola odorata* L., *Urtica dioica* L., *Chelidonium majus* L., *Alliaria petiolate* (M.Bieb.) Cavara & Grande. Soil profile description: Ah1 (0–10 cm), Ah2 (10–34 cm), Ah3 (34–54 cm), Bt (54–92 cm), Bk (92–120 cm), Ck (120–150 cm+). The soil is a Luvic Chernozem.

Fig. 1. Location of the sites (Dnipropetrovsk oblast, Ukraine):
1 – areas 1 (ordinary chernozem under steppe vegetation), 4 (ordinary chernozem under acacia planting), 7 (ordinary chernozem under oak plantation), 10 (luvic chernozem under natural forest vegetation); 2 – areas 2 (ordinary chernozem under steppe vegetation), 5 (ordinary chernozem under acacia planting), 8 (ordinary chernozem under oak plantation); 3 – areas 3 (ordinary chernozem under steppe vegetation), 6 (ordinary chernozem under acacia planting), 9 (ordinary chernozem under oak plantation); 4 – areas 11 and 12 (luvic chernozems under natural forest vegetation)

Sample procedures. About 1 kg of composite soil sample was selected at each of the 12 sites. The physical properties of soils were determined in the formally selected layers of the profile: 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Research was conducted during the years 2017 to 2020. Soil samples selected were later used for laboratory determination of their physical properties.

Laboratory analyses. The field description of soil profiles was conducted in accordance with the "Guidelines for soil description" (FAO, 2006). The classification position of the studied soils was determined as per the International Union of Soil Science Working Group on the World Reference Base 2015. Air-dried soil samples were used for laboratory studies.

Particle size distribution, aggregate-size distribution, size distribution of water-stable aggregates, bulk density, particle density, total porosity of soils were determined in accordance with the "Soil Sampling and Methods of Analysis" (Carter & Gregorich, 2008). The soil particle size distribution of the soil was determined by the pipette method, with a 4% sodium pyrophosphate solution ($Na_4P_2O_7$) used as a dispersant. Aggregate size distribution of soils was determined by dry sieving through a standard set of sieves of 10, 7, 5, 3, 2, 1, 0.50 and 0.25 mm mesh, size distribution of water-stable aggregates was determined by sieving in water and the results were expressed as a percentage of the mass of fractions of different sizes to the mass of the total soil sample. Bulk density (Db) was defined as the weight of soil particles divided by the total soil volume. For this purpose, field soil samples of about 1000 cm^3 each were taken with a hand probe, followed by weighing in the laboratory with parallel determination of field humidity. Particle density (Dp) was determined using a glass pycnometer with a volume of 100 cm^3 and 10 g of soil sample. The total porosity was calculated using the particle density and bulk density values as $(1 - Db/Dp) \times 100$. Plant available water is defined as the difference between the water-holding capacity and water content at wilting point (de Melo et al., 2023). The study relied on soil samples with broken structure to determine the water-holding capacity and water permeability. The prepared sample was placed in a glass tube of known mass, compacted and saturated with water from above. After removing the gravitational water, the sample was weighed. By calculating the difference in mass between the dry and wet samples, the water-holding capacity values were obtained (Vadyunina & Korchahina, 1986). The water content at wilting point was calculated by multiplying the maximum hygroscopic moisture by 1.34 (Medvedev et al., 2011). The maximum hygroscopic moisture was determined by saturating a soil sample weighing 10 g saturated with atmospheric moisture (at 96–98% relative air humidity) over a 10% H_2SO_4 solution until a constant mass was achieved. The sample was then dried for 6 h at a temperature of 105 °C. The ratio of the saturation moisture to the absolutely dry mass, expressed as a percentage, was used as the value of the maximum hygroscopic moisture (Vadyunina & Korchahina, 1986).

Specific electrical resistivity of soil was studied by measuring current and voltage in pastes using a cuvette with a four-electrode sensor (Pozdnyakov, 2008). Determination of the dielectric constant of soils was carried out using a capacitance meter CM-9601A (Korea), which provides measurement of the capacitance of the capacitor in a wide range – from 10^{-12} to 10^{-3} farads. We used a working range of 0.1–200 pF, the test frequency was 800 Hz. To measure the dielectric constant, a cylindrical capacitor made of plexiglass was used. The diameter of the capacitor covers was 2 cm, the distance between them was 0.7 cm. The soil for the study was used in an air-dry state to level out the effects of moisture, the content of which has a significant effect on the dielectric constant (Zhao et al., 2023).

Statistical analysis. All measurements of the physical properties of soils were carried out in nine repetitions. The data obtained were analyzed using Statistica 12.0 (StatSoft Inc., 2013, USA) and OriginPro 9.1 (OriginLab, 2013, USA). The results were tabulated as x ± SD (standard deviation). The differences between the values of the control and experimental groups were determined using the Tukey test, with statistical significance considered at P < 0.05 (taking into account the Bonferroni correction). Data grouping was carried out using cluster analysis (Complete Linkage, Euclidean distances).

Results

The influence of forest vegetation on the particle size distribution of chernozems. As a result of the study, it was established that the minimum sand content is typical for ordinary chernozems under steppe vegetation, especially in layers of 60–80 and 80–100 cm (9.2% and 9.4%, respectively). The growth of *R. pseudoacacia* and *Q. robur* plantations on ordinary chernozems and natural forest vegetation on luvic chernozems contributes to an increase in the sand content in them compared to ordinary chernozems under steppe vegetation (Table 1). The most contrasting changes are observed in the surface layer of 0–20 cm. For all studied chernozems, the maximum sand content is typical for the layer of 0–20 cm; its content gradually decreases with depth.

Table 1
Particle size distribution of chernozems (x ± SD, n = 9)

Particle size	Depth, cm	Calcic Chernozem under steppe vegetation, %	Calcic Chernozem under *R. pseudoacacia* plantation, %	Calcic Chernozem under *Q. robur* plantation, %	Luvic Chernozem under natural forest vegetation, %
Sand	0–20	15.4 ± 7.9	20.8 ± 9.8	20.3 ± 7.1	19.0 ± 3.7
	20–40	14.5 ± 6.0	17.9 ± 10.0	19.1 ± 7.0	18.0 ± 3.3
	40–60	11.4 ± 4.0	15.8 ± 9.7	16.0 ± 3.1	17.6 ± 1.8
	60–80	9.2 ± 3.9	15.5 ± 8.4	11.4 ± 6.5	15.5 ± 1.4
	80–100	9.4 ± 4.7	15.1 ± 7.7	11.7 ± 5.9	15.8 ± 2.5
Silt	0–20	58.7 ± 7.4	53.5 ± 8.6	54.7 ± 6.9	63.3 ± 2.8
	20–40	57.5 ± 8.4	56.0 ± 11.5	55.4 ± 7.4	61.8 ± 4.4
	40–60	59.4 ± 8.8	57.3 ± 13.3	56.1 ± 7.3	60.8 ± 8.2
	60–80	60.5 ± 9.8	55.3 ± 8.4	58.6 ± 8.0	62.7 ± 7.7
	80–100	59.4 ± 3.8	55.3 ± 7.2	59.2 ± 8.9	61.8 ± 7.2
Clay	0–20	25.9 ± 11.6	25.7 ± 4.5	25.1 ± 6.6	17.7 ± 1.0
	20–40	28.0 ± 12.6	26.1 ± 6.2	25.5 ± 7.4	20.2 ± 5.2
	40–60	29.3 ± 12.6	27.0 ± 7.2	27.9 ± 5.9	21.7 ± 9.0
	60–80	30.4 ± 13.5	29.2 ± 4.9	30.0 ± 8.1	21.8 ± 8.7
	80–100	31.2 ± 12.0	29.6 ± 6.9	29.1 ± 11.3	22.4 ± 9.7

Note: using the Tukey test, with statistical significance considered at P < 0.05 (taking into account the Bonferroni correction) did not reveal significant differences between the studied values.

The maximum silt content (63.3%) was found in the upper 0–20 cm layer of luvic chernozems. Ordinary chernozems under acacia and oak plantations are characterized by minimal silt content. The difference between the silt content in the studied chernozems is especially clear in the upper layer of 0–20 cm. The maximum clay content (31.2%) was found in ordinary chernozems under steppe vegetation in a layer of 80–100 cm. Luvic chernozems are characterized by a minimum clay content (17.7%) in a layer of 0–20 cm. In all chernozems, an increase in clay content is observed with depth. As a result of cluster analysis, it was established that the data can be conditionally divided into two groups (Fig. 2): the first group includes the sand content in all studied chernozems (SaS, SaR, SaQ and SaN), the second – the silt content (SiS, SiR, SiQ and SiN) and clays (ClS, ClR, ClQ and ClN). Analysis of variance confirmed a significant difference between the studied chernozems in the content of silt (F = 3.63, P = 0.04) and clay (F = 12.02, P = $1.7 \cdot 10^{-4}$).

The influence of forest vegetation on the aggregate-size distribution and size distribution of water-stable aggregates of chernozems. Studies of the aggregate composition (Table 2) have established that the maximum content of aggregates of the fraction > 10 mm is found in layers of 60–80 and 80–100 cm of luvic chernozems (37.6% and 37.9%, respectively). The minimum content of aggregates of this fraction was found in the 0–20 cm layer of ordinary chernozems under oak plantations (4.1%). The growth of acacia and oak plantations contributes to a decrease in the content of aggregates of the > 10 mm fraction in the 20–40 and 40–60 cm layers of ordinary chernozems. The influence of natural forest vegetation led to an increase in the content of this fraction of aggregates in all layers of chernozems.

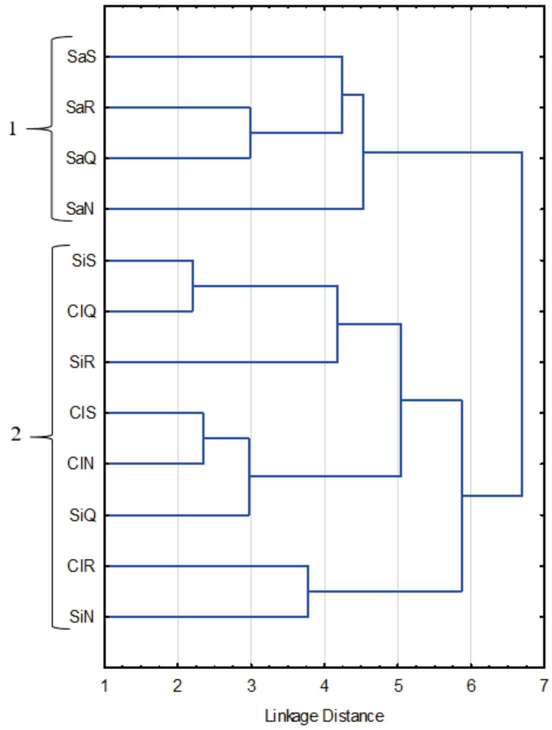

Fig. 2. Results of cluster analysis (Complete Linkage, Euclidean distances) of data on the content of sand (Sa), silt (Si) and clay (Cl) in ordinary chernozems under steppe vegetation (S), plantings of *R. pseudoacacia* (R) and *Q. robur* (Q), in luvic chernozems under natural forest vegetation (N)

The maximum content of aggregates of the 7–10 mm fraction was found in layers of 40–60 and 60–80 cm of ordinary chernozems under steppe vegetation (21.1% and 22.6%, respectively), and the minimum content of this fraction of aggregates was found in the layer of 40–60 cm of luvic chernozems (10.0%). The growth of artificial and natural forest vegetation contributes to a decrease in the content of aggregates of the 7–10 mm fraction in the layers of 20–40, 40–60 and 60–80 cm of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 5–7 mm fraction was found in layers of 40–60 and 60–80 cm of ordinary chernozems under oak plantations (16.2% and 16.3%, respectively), and the minimum content of aggregates of this fraction is associated with a layer of 0–20 cm of chernozems common under steppe vegetation (9.2%). The growth of artificial and natural forest vegetation contributes to an increase in the content of aggregates of the 5–7 mm cm fraction in the 0–20 cm layer of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 3–5 mm fraction was found in layers of 20–40 and 40–60 cm of luvic chernozems (13.1% and 13.5%, respectively). The minimum content of this fraction of aggregates was also found in luvic chernozems, in the layer of 80–100 cm (7.6%). The growth of artificial and natural forest vegetation contributes to an increase in the content of aggregates of the 3–5 mm fraction in the layers of 0–20, 20–40 and 40–60 cm of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 2–3 mm fraction was found in the 0–20 cm layer of luvic chernozems (16.9%). The minimum content of this aggregate fraction was also found in these soils, in the 80–100 cm layer (8.7%). The growth of artificial and natural forest vegetation contributes to an increase in the content of aggregates of the 2–3 mm fraction in the layers of 0–20, 20–40 and 40–60 cm of ordinary chernozems and luvic chernozems.

Table 2
Aggregate size distribution of chernozems (x ± SD, n = 9)

Aggregate size, mm	Depth, cm	Calcic Chernozem under steppe vegetation, %	Calcic Chernozem under *R. pseudoacacia* plantation, %	Calcic Chernozem under *Q. robur* plantation, %	Luvic Chernozem under natural forest vegetation, %
> 10	0–20	6.7 ± 3.4	6.9 ± 3.8	4.1 ± 2.7	9.1 ± 4.5
	20–40	11.3 ± 6.8	7.0 ± 3.2	7.0 ± 4.0	14.8 ± 7.1
	40–60	14.4 ± 7.8	9.8 ± 4.4	10.9 ± 6.1	19.7 ± 10.7
	60–80	17.5 ± 8.4	17.6 ± 6.3	9.6 ± 5.1	37.6 ± 6.1
	80–100	5.4 ± 3.2	12.0 ± 4.7	14.1 ± 5.2	37.9 ± 4.8
7–10	0–20	9.5 ± 4.7	14.0 ± 2.9	10.4 ± 5.1	13.3 ± 6.7
	20–40	17.9 ± 6.3	14.7 ± 6.8	10.4 ± 3.2	10.0 ± 5.2
	40–60	21.1 ± 3.9	12.9 ± 6.7	15.7 ± 0.9	10.0 ± 5.1
	60–80	22.6 ± 3.9	20.2 ± 5.5	18.9 ± 3.5	13.5 ± 2.4
	80–100	17.9 ± 8.9	16.0 ± 2.6	20.6 ± 6.9	13.4 ± 2.8
5–7	0–20	9.2 ± 1.2	12.7 ± 2.3	12.6 ± 5.2	13.1 ± 6.4
	20–40	12.8 ± 2.2	13.1 ± 0.8	12.4 ± 2.9	11.2 ± 2.4
	40–60	14.2 ± 3.1	16.1 ± 2.1	16.2 ± 6.3	11.2 ± 1.6
	60–80	15.0 ± 5.9	14.0 ± 2.6	16.3 ± 6.2	11.0 ± 1.7
	80–100	15.1 ± 2.1	12.9 ± 2.0	14.2 ± 1.6	10.9 ± 2.1
3–5	0–20	9.6 ± 3.3	12.3 ± 1.9	12.1 ± 2.3	12.9 ± 2.0
	20–40	11.0 ± 2.1	12.0 ± 2.3	12.5 ± 1.2	13.1 ± 6.6
	40–60	11.0 ± 2.3	12.0 ± 2.7	13.0 ± 4.8	13.5 ± 7.3
	60–80	11.1 ± 2.5	9.3 ± 2.4	12.9 ± 4.8	8.8 ± +1.0
	80–100	11.7 ± 2.4	8.6 ± 1.9	10.8 ± 2.4	7.6 ± 1.5
2–3	0–20	13.6 ± 5.6	16.8 ± 1.5	16.0 ± 1.5	16.9 ± 8.4
	20–40	13.7 ± 5.5	15.8 ± 4.0	15.3 ± 2.1	16.7 ± 9.9
	40–60	12.9 ± 5.2	14.1 ± 4.0	14.9 ± 5.4	16.0 ± 9.3
	60–80	12.4 ± 5.4	11.4 ± 4.8	14.3 ± 4.6	9.4 ± 1.5
	80–100	15.2 ± 4.8	11.0 ± 2.9	11.6 ± 1.4	8.7 ± 1.9
1–2	0–20	18.9 ± 5.7	18.8 ± 5.6	19.2 ± 5.4	16.8 ± 8.7
	20–40	15.1 ± 6.4	15.8 ± 2.2	17.9 ± 4.6	15.4 ± 5.3
	40–60	12.4 ± 3.7	13.9 ± 3.2	13.0 ± 3.3	13.8 ± 5.4
	60–80	10.9 ± 3.4	10.0 ± 2.6	12.7 ± 0.9	8.9 ± 2.6
	80–100	16.4 ± 6.7	12.7 ± 2.4	11.1 ± 0.8	8.6 ± 2.5
0.5–1.0	0–20	15.9 ± 4.4	10.9 ± 3.6	14.3 ± 5.6	9.7 ± 3.3
	20–40	9.4 ± 2.2	10.9 ± 2.0	12.9 ± 4.4	9.5 ± 0.8
	40–60	7.4 ± 0.94	10.3 ± 3.5	7.7 ± 1.7	8.0 ± 2.0
	60–80	5.9 ± 0.6	6.8 ± 2.5	7.1 ± 2.1	6.2 ± 2.3
	80–100	9.1 ± 1.1	10.3 ± 1.6	7.6 ± 2.7	6.2 ± 1.7
0.25–0.50	0–20	9.2 ± 2.0	4.3 ± 2.2	6.0 ± 3.0	3.8 ± 0.5
	20–40	4.8 ± 1.9	5.4 ± 2.7	6.0 ± 2.9	4.3 ± 0.6
	40–60	3.7 ± 1.0	5.7 ± 4.0	4.4 ± 2.6	3.3 ± 1.3
	60–80	2.5 ± 0.8	4.3 ± 3.3	3.9 ± 2.0	2.7 ± 1.5
	80–100	4.4 ± 0.2	7.6 ± 3.0	4.6 ± 1.9	3.0 ± 0.4
< 0.25	0–20	7.3 ± 1.4	3.4 ± 1.3	5.3 ± 2.2	4.5 ± 1.9
	20–40	4.1 ± 2.1	5.4 ± 3.2	5.6 ± 3.4	5.1 ± 1.8
	40–60	3.1 ± 0.8	5.2 ± 3.4	4.2 ± 2.1	4.7 ± 2.5
	60–80	2.2 ± 1.2	6.5 ± 5.8	4.3 ± 2.8	1.9 ± 1.6
	80–100	4.9 ± 2.3	9.0 ± 4.1	5.4 ± 3.2	3.7 ± 2.0

Note: see Table 1.

The maximum content of aggregates of the 3–5 mm fraction was found in layers of 20–40 and 40–60 cm of luvic chernozems (13.1 and 13.5%, respectively). The minimum content of this fraction of aggregates was also found in luvic chernozems, in the layer of 80–100 cm (7.6%). The growth of artificial and natural forest vegetation contributes to an increase in the content of aggregates of the 3–5 mm fraction in the layers of 0–20, 20–40 and 40–60 cm of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 2–3 mm fraction was found in the 0–20 cm layer of luvic chernozems (16.9%). The minimum content of this aggregate fraction was also found in these soils, in the 80–100 cm layer (8.7%). The growth of artificial and natural forest vegetation contributed to an increase in the content of aggregates of the 2–3 mm fraction in the layers of 0–20, 20–40 and 40–60 cm of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 1–2 mm fraction was found in the layer of 0–20 cm of ordinary chernozems under oak plantations (19.2%), and the minimum content of this fraction of aggregates was found in layers of 60–80 and 80–100 cm of luvic chernozems (8.9% and 8.6% respectively). The growth of forest vegetation did not lead to significant changes in the distribution of aggregates of the 1–2 mm fraction across the layers of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the 0.5–1.0 mm fraction was found in the 0–20 cm layer of ordinary chernozems under steppe vegetation (15.9%). The minimum content of this fraction of aggregates was also found in ordinary chernozems under steppe vegetation, in the layer of 60–80 cm (5.9%). The growth of artificial and natural forest vegetation contributed to a decrease in the content of aggregates of the 0.5–1.0 mm fraction in the 0–20 cm layer of ordinary chernozems and luvic chernozems. The maximum content of aggregates of the 0.25–0.50 mm fraction was found in the 0–20 cm layer of ordinary chernozems under steppe vegetation (9.2%). The minimum content of this fraction of aggregates was also found in ordinary chernozems under steppe vegetation, in the layer of 60–80 cm (2.5%). The growth of artificial and natural forest vegetation contributes to a decrease in the content of aggregates of the 0.25–0.50 mm fraction in the 0–20 cm layer of ordinary chernozems and luvic chernozems.

The maximum content of aggregates of the <0.25 mm fraction was found in the layer of 80–100 cm of ordinary chernozems under acacia plantations (9.0%), and the minimum content of this fraction of aggregates was found in the layer of 60–80 cm of luvic chernozems (1.9%). The growth of artificial and natural forest vegetation contributes to a decrease in the content of fraction aggregates <0.25 mm in the 0–20 cm layer and an increase in the 20–40 and 40–60 cm layers of ordinary chernozems and luvic chernozems.

Analysis of variance confirmed a significant difference in the studied chernozems in the content of aggregates of fractions > 10 mm ($F = 11.18$, $P = 3.1 \cdot 10^{-4}$) and 5–7 mm ($F = 5.73$, $P = 8.7 \cdot 10^{-3}$).

Studies of water-resistant aggregates of chernozems (Table 3) revealed that the maximum content of their fraction > 5 mm was found in the 0–20 cm layer of chernozem luvisol (11.1%). The growth of artificial and natural forest vegetation on chernozems has led to an increase in the content of water-resistant aggregates of the fraction > 5 mm, and this is most clearly manifested in luvic chernozems.

The maximum content of water-resistant aggregates of the 3–5 mm fraction was also found in the 0–20 cm layer of luvic chernozem (8.4%). In ordinary chernozems under acacia and oak plantations, an increase in the content of this fraction is also observed compared to ordinary chernozems under steppe vegetation.

The maximum content of water-resistant aggregates of the 2–3 mm fraction was found in the 0–20 cm layer of ordinary chernozems under oak plantations (9.6%). Ordinary chernozems under acacia plantations and luvic chernozems under natural forest vegetation are also characterized by an increased content of this fraction compared to ordinary chernozems under steppe vegetation.

The maximum content of water-resistant aggregates of the 1–2 mm fraction was detected in the 0–20 cm layer of ordinary chernozems under oak and acacia plantations (16.8% and 12.9%, respectively). In luvic chernozem, the content of this fraction is also higher than in ordinary chernozems under steppe vegetation.

The maximum content of water-resistant aggregates of the 0.5–1.0 mm fraction was found in the layer of 20–40 cm of ordinary chernozems under oak plantations (25.3%). Ordinary chernozems under artificial forest plantations and luvic chernozems under natural vegetation are characterized by an increased content of this fraction compared to ordinary chernozems under steppe vegetation.

The maximum content of water-resistant aggregates of the 0.25–0.50 mm fraction was found in the layer of 80–100 cm of ordinary chernozems under oak plantations (30.8%). The growth of artificial and natural forest plantations contributes to a decrease in the content of this fraction in the layers of 0–20, 20–40 and 40–60 cm of ordinary chernozems and luvic chernozems.

The maximum content of water-resistant aggregates of the <0.25 mm fraction was found in the 80–100 cm layer of luvic chernozems (59.4%). The growth of artificial and natural forest plantations contributes to a decrease in the content of this fraction in the 0–20 and 20–40 cm layers of ordinary chernozems and luvic chernozems. As a result of cluster analysis, it was found that the data can be conditionally divided into 4 groups (Fig. 3): the first group includes the content of water-resistant aggregates of fractions 1– > 5 mm (S(>5), S(3–5), S(2 –3), R(3–5), N(3–5), N(2–3), N(1–2), Q(1–2)), to the second – content of water-resistant fraction aggregates < 0.25– 2 mm (S(1–2), S(0.5–1), N(0.5–1), S(0.25–0.5), N(0.25–0.5), Q(<0.25), R(0.25–0.5), N(<0.25), Q(0.25–0.50), R(<0.25)), to the third – the content of water-resistant aggregates of fractions 2– > 5 mm (R(>5), N(>5), R(2–3), Q(2–3), Q(>5), Q(3–5)), to the fourth – the content of water-resistant aggregates of fractions < 0.25–2 mm (R(1–2), R(0.5–1), S(<0.25), Q(0.5–1)). Among the 4 groups identified according to the size of fractions of water-resistant aggregates, the first can be combined with the third (fractions 1–> 5 mm), and the second with the fourth (fractions < 0.25–2 mm).

Table 3
Size distribution of water-stable aggregates of chernozems (x ± SD, n = 9)

Aggregate size, mm	Depth, cm	Calcic Chernozem under steppe vegetation, %	Calcic Chernozem under *R. pseudoacacia* plantation, %	Calcic Chernozem under *Q. robur* plantation, %	Luvic Chernozem under natural forest vegetation, %
> 5	0–20	1.032 ± 0.544	3.578 ± 1.702	7.253 ± 2.430	11.123 ± 3.551
	20–40	0.634 ± 0.208	0.525 ± 0.290	1.176 ± 0.569	2.985 ± 0.616
	40–60	0.271 ± 0.031	0.302 ± 0.165	0.338 ± 0.193	1.082 ± 0.533
	60–80	0.176 ± 0.014	0.073 ± 0.024	0.031 ± 0.002	0.303 ± 0.124
	80–100	0.177 ± 0.092	0.000 ± 0.000	0.000 ± 0.000	0.358 ± 0.113
3–5	0–20	2.085 ± 0.719	4.322 ± 1.677	5.605 ± 2.045	8.408 ± 2.634
	20–40	1.024 ± 0.202	0.723 ± 0.161	1.702 ± 0.265	2.253 ± 0.752
	40–60	0.678 ± 0.153	0.138 ± 0.058	0.803 ± 0.229	1.272 ± 0.332
	60–80	0.379 ± 0.085	0.182 ± 0.032	0.378 ± 0.063	0.876 ± 0.335
	80–100	0.231 ± 0.100	0.271 ± 0.150	0.201 ± 0.085	0.835 ± 0.278
2–3	0–20	2.775 ± 1.176	6.527 ± 1.336	9.605 ± 3.709	7.978 ± 2.206
	20–40	2.302 ± 1.039	1.781 ± 0.501	4.000 ± 0.917	3.475 ± 2.501
	40–60	2.276 ± 1.002	1.235 ± 0.577	2.837 ± 0.973	1.936 ± 2.515
	60–80	1.938 ± 0.578	0.906 ± 0.461	1.335 ± 0.312	1.071 ± 1.686
	80–100	0.901 ± 0.401	0.633 ± 0.352	0.837 ± 0.403	1.082 ± 1.584
1–2	0–20	7.025 ± 3.300	12.889 ± 2.181	16.779 ± 4.119	9.778 ± 1.239
	20–40	6.956 ± 2.871	7.326 ± 3.415	12.108 ± 4.521	6.224 ± 2.323
	40–60	7.835 ± 3.612	7.378 ± 3.329	10.300 ± 2.848	4.405 ± 2.193
	60–80	8.604 ± 2.868	4.824 ± 2.888	6.305 ± 1.956	3.173 ± 1.128
	80–100	5.000 ± 1.912	3.077 ± 3.024	4.701 ± 2.704	2.632 ± 1.102
0.5–1.0	0–20	12.333 ± 7.314	22.256 ± 4.401	20.000 ± 5.953	16.900 ± 1.097
	20–40	15.434 ± 6.921	22.785 ± 8.563	25.300 ± 5.693	21.828 ± 6.503
	40–60	18.608 ± 5.240	21.106 ± 8.244	18.835±10.125	19.684 ± 7.653
	60–80	22.130 ± 5.861	15.684 ± 6.107	17.588 ± 8.598	14.676 ± 5.588
	80–100	16.174 ± 4.744	10.378 ± 4.442	16.676 ± 8.127	12.424 ± 5.733
0.25–0.50	0–20	21.185 ± 3.509	18.884 ± 2.094	14.986 ± 4.686	15.426 ± 3.157
	20–40	24.332 ± 4.304	24.186 ± 1.353	22.501 ± 3.897	22.136 ± 0.862
	40–60	24.233 ± 1.155	23.734 ± 2.491	22.776 ± 2.574	24.280 ± 4.330
	60–80	24.802 ± 3.82	30.382 ± 7.354	27.784 ± 3.022	27.479 ± 5.733
	80–100	29.336 ± 3.82	28.536 ± 8.714	30.806 ± 4.132	23.278 ± 5.294
< 0.25	0–20	53.588±3.509	31.586±2.094	25.804±4.686	30.431±3.157
	20–40	49.333±10.610	42.705±11.605	33.236±3.544	41.130±13.590
	40–60	46.135±7.547	46.137±12.579	44.132±9.152	47.355±15.355
	60–80	42.000±8.552	47.970±13.600	46.603±6.511	52.479±14.053
	80–100	48.200±7.634	57.134±19.626	46.808±14.172	59.422±15.144

Note: see Table 1.

Analysis of variance confirmed a significant difference in the studied chernozems in the content of water-resistant aggregates of fractions > 5 mm (F = 4.38, P = 0.020), 3–5 mm (F = 6.80, P = $4.2 \cdot 10^{-3}$) and 1–2 mm (F = 10.80, P = $3.9 \cdot 10^{-4}$).

The influence of forest vegetation on bulk density, particle density, total porosity of chernozems. The results of the study of the density of chernozems (Table 4) indicate that in the 0–20 cm layer its maximum value was found in ordinary chernozems under steppe vegetation (1.164 g/cm^3), and the minimum in luvic chernozems under natural forest vegetation (1.029 g/cm^3). The influence of forest vegetation on chernozems, which manifests itself in a decrease in their density, is most clearly manifested in layers of 0–20 and 20–40 cm. In layers of 40–60, 60–80 and 80–100 cm, differences between chernozems under steppe vegetation and chernozems under forest vegetation are practically leveled out.

The maximum values of solid phase density were found in the layer of 80–100 cm of ordinary chernozems under steppe vegetation and under acacia plantations (2.602 and 2.603 g/cm^3, respectively), and the minimum value was found in the layer of 0–20 cm of luvic chernozems under natural forest vegetation (2.342 g/cm^3). The growth of forest vegetation contributes to a decrease in the density of the solid phase of chernozems, while the most pronounced changes are observed in luvic chernozems, which formed under natural forest vegetation.

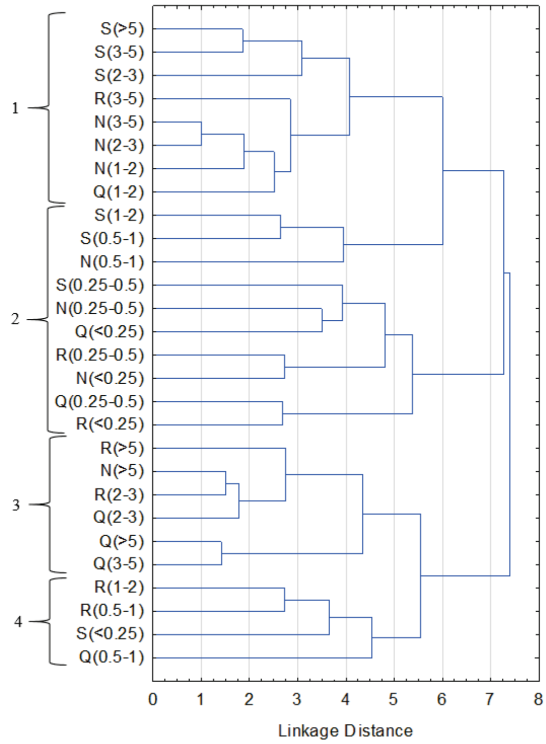

Fig. 3. Results of cluster analysis (Complete Linkage, Euclidean distances) of data on the content of water-resistant aggregates of fractions > 5, 3–5, 2–3, 1–2, 0.5–1.0, 0.25–0.50 and < 0.25 mm in ordinary chernozems under steppe vegetation (S), stands of *R. pseudoacacia* (R) and *Q. robur* (Q), in luvic chernozems under natural forest vegetation (N)

Table 4
Total porosity, bulk and particle density of chernozems (x ± SD, n = 9)

Characteristic	Depth, cm	Calcic Chernozem under steppe vegetation	Calcic Chernozem under *R. pseudoacacia* plantation	Calcic Chernozem under *Q. robur* plantation	Luvic Chernozem under natural forest vegetation
Bulk density, g/cm^3	0–20	1.164 ± 0.072	1.113 ± 0.071	1.086 ± 0.062	1.029 ± 0.043
	20–40	1.255 ± 0.105	1.209 ± 0.083	1.169 ± 0.093	1.144 ± 0.078
	40–60	1.300 ± 0.090	1.296 ± 0.042	1.260 ± 0.070	1.245 ± 0.135
	60–80	1.355 ± 0.075	1.403 ± 0.081	1.315 ± 0.045	1.363 ± 0.061
	80–100	1.433 ± 0.071	1.446 ± 0.081	1.395 ± 0.055	1.486 ± 0.058
Particle density, g/cm^3	0–20	2.476 ± 0.074	2.446 ± 0.082	2.435 ± 0.055	2.342 ± 0.034
	20–40	2.523 ± 0.081	2.492 ± 0.094	2.476 ± 0.062	2.418 ± 0.026
	40–60	2.534 ± 0.086	2.517 ± 0.097	2.506 ± 0.072	2.456 ± 0.006
	60–80	2.578 ± 0.104	2.554 ± 0.092	2.559 ± 0.046	2.478 ± 0.010
	80–100	2.602 ± 0.098	2.603 ± 0.061	2.580 ± 0.060	2.507 ± 0.021
Total porosity, %	0–20	52.99 ± 1.35	54.64 ± 2.42	55.76 ± 1.80	56.71 ± 1.85
	20–40	50.34 ± 2.50	51.98 ± 3.09	52.91 ± 2.89	52.91 ± 3.58
	40–60	48.80 ± 1.83	48.53 ± 2.99	49.67 ± 1.43	49.48 ± 5.56
	60–80	47.31 ± 1.57	44.85 ± 3.21	48.53 ± 0.88	45.11 ± 2.74
	80–100	45.27 ± 1.10	44.67 ± 3.25	46.33 ± 1.43	40.92 ± 1.79

Note: see Table 1.

The maximum value of total porosity was found in the 0–20 cm layer of luvic chernozems (56.7%), and the minimum – in the 80–100 cm layer of the same soils (40.9%). The most pronounced influence of forest vegetation, which causes an increase in the total porosity of chernozems, manifests itself in layers of 0–20 and 20–40 cm; with depth this influence is practically leveled out.

Analysis of variance confirmed a significant difference in the studied chernozems in terms of solid phase density (F = 7.76, P = $2.3 \cdot 10^{-3}$).

The influence of forest vegetation on plant available water and water permeability of chernozems. The study of the water-physical properties of chernozems (Table 5) found that the maximum content of water available for plants is typical for the 0–20 cm layer of chernozems (40.3%), and the minimum is for the 80–100 cm layer of ordinary chernozems under steppe vegetation (25.1%). In all studied chernozems, the upper layers are characterized by an increased content of water available for plants compared to the underlying layers.

Table 5
Water-physical properties of chernozems (x ± SD, n = 9)

Characteristic	Depth, cm	Calcic Chernozem under steppe vegetation	Calcic Chernozem under *R. pseudoacacia* plantation	Calcic Chernozem under *Q. robur* plantation	Luvic Chernozem under natural forest vegetation
Available water for plants, %	0–20	31.6 ± 1.2	33.3 ± 4.7	31.7 ± 3.8	40.3 ± 3.6
	20–40	27.6 ± 5.0	32.2 ± 4.6	30.9 ± 4.6	37.9 ± 2.0
	40–60	27.1 ± 6.4	31.4 ± 5.1	28.6 ± 2.5	35.7 ± 0.7
	60–80	26.1 ± 7.4	31.8 ± 5.8	27.9 ± 3.7	33.7 ± 0.5
	80–100	25.1 ± 5.5	32.5 ± 6.0	28.3 ± 4.0	32.8 ± 1.0
Water permeability, mm/hour	0–20	73.5 ± 15.6	81.2 ± 22.8	82.2 ± 21.4	106.3 ± 7.3
	20–40	56.2 ± 18.5	63.9 ± 26.2	68.1 ± 22.9	84.6 ± 1.5
	40–60	53.4 ± 18.7	62.2 ± 20.3	51.9 ± 18.8	75.0 ± 2.2
	60–80	59.0 ± 13.8	64.9 ± 22.7	56.8 ± 25.5	65.3 ± 3.4
	80–100	53.2 ± 9.4	73.6 ± 29.1	62.7 ± 21.1	59.5 ± 8.2

Note: see Table 1.

The maximum value of water permeability was found in the 0–20 cm layer of luvic chernozems (106.3 mm/hour), the minimum – in the 40–60 cm layer of ordinary chernozems under oak plantations (51.9 mm/hour). The positive effect of forest plantings of acacia and oak on ordinary chernozems and natural forest vegetation on luvic chernozems, which manifests itself in an increase in their water permeability, is most pronounced in the layers of 0–20 and 20–40 cm.

Analysis of variance confirmed a significant difference between the studied chernozems in the amount of water available for plants ($F = 22.56$, $P = 2.1 \cdot 10^{-6}$).

The influence of forest vegetation on the electrical resistivity and dielectric constant of chernozems. As a result of the study of the electrical properties of chernozems (Table 6), it was established that the maximum value of electrical resistivity is observed in the layer of 20–40 cm of ordinary chernozems under acacia plantations (5.103 Ohm m), and the minimum value is in the layer of 80–100 cm of luvic chernozems (2.994 Ohm m). The Tukey test revealed a significant difference in the electrical resistivity of chernozems in the 60–80 cm layer.

Table 6
Electro-physical properties of chernozems (x ± SD, n = 9)

Characteristic	Depth, cm	Calcic Chernozem under steppe vegetation	Calcic Chernozem under *R. pseudoacacia* plantation	Calcic Chernozem under *Q. robur* plantation	Luvic Chernozem under natural forest vegetation
Specific electrical resistivity, Ohm.m	0–20	4.06 ± 1.74^{a}	4.76 ± 1.58^{a}	4.01 ± 1.45^{a}	3.28 ± 0.62^{a}
	20–40	4.21 ± 1.51^{a}	5.10 ± 1.80^{a}	4.58 ± 1.09^{a}	3.58 ± 0.64^{a}
	40–60	4.08 ± 1.01^{a}	4.27 ± 1.07^{a}	4.85 ± 2.19^{a}	3.42 ± 0.63^{a}
	60–80	3.66 ± 1.75^{a}	4.43 ± 1.04^{ab}	4.77 ± 1.96^{ac}	3.22 ± 0.81^{ad}
	80–100	3.99 ± 1.28^{a}	4.58 ± 1.00^{a}	4.60 ± 2.33^{a}	2.99 ± 0.95^{a}
Dielectric constant	0–20	57.4 ± 21.6^{a}	40.4 ± 17.2^{a}	23.9 ± 11.9^{a}	14.6 ± 5.3^{a}
	20–40	72.0 ± 29.2^{a}	60.4 ± 34.3^{a}	33.8 ± 10.2^{ab}	31.3 ± 13.3^{a}
	40–60	74.7 ± 31.2^{a}	74.8 ± 28.7^{a}	55.2 ± 7.9^{ab}	46.2 ± 16.9^{a}
	60–80	84.8 ± 10.3^{a}	77.6 ± 40.7^{ab}	55.6 ± 17.5^{ac}	54.0 ± 14.8^{a}
	80–100	66.2 ± 29.3^{a}	94.3 ± 29.9^{ab}	88.7 ± 24.1^{ac}	65.6 ± 17.8^{a}

Note: different letters denote sets within a range of indicators that differ significantly from each other according to Tukey's Bonferoni-corrected test results; differences between sets were considered significant at $P < 0.05$.

The maximum value of dielectric constant was found in the 80–100 cm layer of ordinary chernozems under acacia plantations (94.3), and the minimum – in the 0–20 cm layer of luvic chernozems (14.6). The growth of forest plantations and natural forest vegetation contributes to a decrease in the dielectric constant of chernozems, and this effect is most clearly observed in layers 0–20, 20–40, 40–60 and 60–80 cm of ordinary chernozems under oak plantations and luvic chernozems under natural forest vegetation. The Tukey test revealed a significant difference in dielectric constant between ordinary chernozems under steppe vegetation and under oak plantations (layers 20–40 and 40–60 cm), as well as between ordinary chernozems under steppe vegetation, under acacia and oak plantations (layers 60–80 and 80–100 cm).

Analysis of variance confirmed a significant difference in the studied chernozems in terms of electrical resistivity ($F = 4.05$, $P = 0.03$) and dielectric constant ($F = 6.92$, $P = 3.9 \cdot 10^{-3}$).

Discussion

Particle size distribution is one of the basic characteristics of soils, which largely determines most other soil properties and features (Shamray & Didur, 2022; Qi et al., 2023). Common chernozems under steppe vegetation, which were used in our work as a control, belong to the silty loam (SiL) textural class. The growth of acacia and oak plantations and natural forest vegetation did not lead to a change in the textural class of ordinary chernozems and luvic chernozems. In ordinary chernozems under acacia and oak plantations, the content of sand and silt increased compared to ordinary chernozems under steppe vegetation. An increase in silt content in chernozems under acacia plantations was also found by Li et al. (2022), and under oak stands by Su et al. (2022). Yu et al. (2023) also notes an increase in silt content in soils during the restoration of forest vegetation. At the same time, all of these authors note a decrease in the sand content in chernozems under the influence of forest vegetation, which is not consistent with the results obtained by us. In luvic chernozems under natural forest vegetation, there is an increased content of sand and silt, a reduced content of clay compared to ordinary chernozems under steppe vegetation. Such features of the granulometric composition of ordinary chernozems and luvic chernozems under forest vegetation can be explained by the supply of aeolian material, which is characterized by an increased content of silt and sand (Avecilla et al., 2023). The results of cluster analysis of data on the content of sand, silt and clay may indicate that changes in the content of silt and clay in chernozems under the influence of forest vegetation are interdependent, unlike sand content.

Aggregate size distribution and aggregate water resistance are important characteristics of soils, which can be used as an indicator of the intensity and duration of the influence of forest vegetation on soils (Jiang et al., 2019), as well as soil resistance to water erosion (Tian et al., 2023). The growth of acacia and oak forest plantations and natural forest vegetation caused an increase in the content of aggregates of fractions 7–10, 5–7, 3–5 and 2–3 mm and a decrease in the content of aggregates of fractions 0.5–1.0, 0.25–0.50 and <0.25 mm in the 0–20 cm layer of ordinary chernozems and luvic chernozems compared to ordinary chernozems under steppe vegetation. Our results are consistent with the results of other scientists. Yang et al. (2024) note an increase in the content of aggregates of the > 2 mm fraction during the restoration of forest vegetation, especially in the 0–40 cm layer. Luo et al. (2023) found an increased content of aggregates of the > 2 mm fraction in forest soils. Thus, the content of aggregates of the fraction > 2 mm can be used as an indicator of the influence of forest vegetation on the aggregate composition of chernozems. The growth of forest plantations and natural forest vegetation on chernozems led to an increase in the content of water-resistant aggregates of fractions > 5, 3–5, 2–3, 1–2 and 0.5–1.0 mm in the 0–20 cm layer and a decrease in the content of fractions 0.25–0.50 and <0.25 mm compared to ordinary chernozems under steppe vegetation. Research results by Liang et al. (2023) also indicate an increase in the content of water-stable aggregates in soils during the restoration of forest vegetation. Cheng et al. (2023) obtained results confirming the predominance of water-stable aggregates in the surface soil layer (0–20 cm) under the forest. The results of cluster analysis of data on the content of water-resistant aggregates may indicate similar mechanisms for the formation of water-resistant aggregates in chernozems under steppe and forest vegetation. The results obtained may indicate an increase in the content of organic substances in ordinary chernozems and luvic chernozems under the influence of forest vegetation, which manifests itself, in particular, in an improvement in the aggregate composition of these soils (Li et al., 2023).

Density, solid density and total porosity are important complex characteristics of soils, which depend on the ratio of sand, silt and clay in the soil, organic matter content and other factors (Chen et al., 2023). The influence of forest vegetation on chernozems led to a decrease in their density and solid phase density, as well as an increase in total porosity, and these changes are most pronounced in the 0–20 and 20–40 cm layers of chernozems under natural forest vegetation. The minimum values of density and maximum values of total porosity of soils under natural forest compared to soils of other land use types were also found by Ayoubi et al. (2020).

Water physical properties reflect the ability of the soil to provide the necessary moisture to plants, animals and microorganisms that are associated with it (Yu et al., 2023). The influence of forest vegetation led to an increase in the content of available water for plants and an increase in water permeability of chernozems of ordinary acacia and oak plantations compared to ordinary chernozems under steppe vegetation. The growth of natural forest vegetation had a more pronounced effect on the studied water-physical properties of chernozem luvisol compared to the influence of plantings on the water-physical properties of ordinary chernozems (Tsvetkova & Saranenko, 2007, 2010; Saranenko, 2011; Tsvetkova et al., 2015). The positive effect of forest plantations on the water-physical properties of soils is confirmed by the results of studies by Kelly & Ray (2023), Parvizi & Fatehi (2024).

The electrical resistivity of soils is largely determined by their moisture content and content of water-soluble salts (Park et al., 2024). The influence of acacia and oak plantings was manifested in an increase in the electrical resistivity of ordinary chernozems compared to ordinary chernozems under steppe vegetation, which indicates the leaching of water-soluble salts from these soils. The growth of natural forest vegetation led to a decrease in the electrical resistivity of luvic chernozems compared to ordinary chernozems under steppe vegetation, which reflects the enrichment of these soils with water-soluble compounds, possibly due to their supply from soils that are located above the studied luvic chernozems on the slope of the ravine. The results obtained indicate a significant influence of forest vegetation on chernozems, since the value of electrical resistivity of soils is practically not affected by changes in the growth of forest plantations (Saeidi et al., 2023) and changes in land use type (Flynn et al., 2023). The influence of forest vegetation led to a decrease in the dielectric constant of ordinary chernozems and luvic chernozems compared to ordinary chernozems under steppe vegetation. These results confirm the positive effect of forest vegetation on the aggregate composition and density of the studied chernozems, the features of which determine the dielectric constant of soils (Stellini et al., 2023; Wan et al., 2023).

Conclusion

Ordinary chernozems under steppe vegetation are classified as Silty loam. The growth of forest vegetation did not lead to a change in the granulometric class (textural class) of chernozems, however, in ordinary chernozems under acacia and oak plantations, an increase in sand content and a decrease in silt content was observed, and in luvic chernozems under natural forest vegetation an increased content of sand and silt and a decreased content of clay were found compared to ordinary chernozems under steppe vegetation. In chernozems under the influence of forest vegetation in the 0–20 cm layer, an increased content of aggregates of fractions 7–10, 5–7, 3–5 and 2–3 mm and a reduced content of aggregates of fractions 0.5–1.0, 0.25–0.50 and <0.25 mm, as well as an increase in the content of water-resistant aggregates of fractions > 5, 3–5, 2–3, 1–2 and 0.5–1.0 mm and a decrease in the content of fractions 0.25–0.50 and < 0.25 mm were observed compared to chernozems under steppe vegetation. The influence of forest vegetation on chernozems causes a decrease in their density and density of the solid phase, as well as an increase in total porosity, especially in layers of 0–20 and 20–40 cm. Chernozems under forest vegetation are characterized by an increased content of available water for plants and increased water permeability compared to chernozems under steppe vegetation. The growth of acacia and oak forest plantations led to an increase in the electrical resistivity of ordinary chernozems, and natural forest vegetation led to a decrease in the electrical resistivity of chernozems. The influence of forest vegetation led to a decrease in the dielectric constant of chernozems compared to chernozems under steppe vegetation. Luvic chernozems under natural forest vegetation are characterized by more pronounced changes in physical properties compared to ordinary chernozems under acacia and oak plantations relative to the physical properties of ordinary chernozems under steppe vegetation. Changes in the content of silt and clay, aggregates of fractions > 10 and 5–7 mm, water-resistant aggregates of fractions > 5, 3–5 and 1–2 mm, solid phase values, available water for plants, electrical resistivity and dielectric constant of the studied chernozems have been reliably confirmed under the influence of forest vegetation.

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