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

V. A. Gorban*, N. A. Bilova**, J. L. Poleva***, A. O. Huslystyi*, O. V. Kotovych*, S. O. Hunko*

*Oles Honchar Dnipro National University, Dnipro, Ukraine
**University of Customs and Finance, Dnipro, Ukraine
***Florida Institute of Technology, Melbourne, USA

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 (Bilova & 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 in the forest belt of South-Western Poland, various chernozem soils, as well as fresh habitats of broad-leaved forests develop on chernozems, as well as on the face of the soil moisture regime.

Lasota et al. (2019) found that the formation of chernozems in Poland is associated with various climatic conditions. In general, fresh and moist deposits of broad-leaved forests develop on chernozems, as well as moss habitats of high-mountain broad-leaved forests, which are associated with many species broad-leaved forest stands. In the work of Labaz 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.

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 conditions using soil samples taken from 12 areas established within Dnipropetrovsk region (Ukraine). As a result of the study, 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).


Keywords: granulometric composition; density; available water for plants; ordinary chernozems; oak plantings; forest vegetation.
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 (Symyk 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 L. 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 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 & Hulyasty, 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′33″ E) was located within the virgin steppe land of a watershed plateau. Herbaceous vegetation covered was closed, consists of Festuca valesiaca Schlech. ex Gaudin, Koeleria macrantha (Ledeb.) Schult., Thymus marschallianus Wild., Linum hirsutum L., Salvia nemorosa L., Artemisia austriaca Jacc. and other herbaceous plant species. Soil profile description: A1 (0–7 cm), A2 (7–26 cm), Bk (26–42 cm), Bk2 (42–57 cm). The soil is a Calcic Chernozem.

Site 2 (48°32′29″ N 33°54′40″ E) was located in an anarble 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 anarble 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 a woodland 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. predominated 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 woodland 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. predominated 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°53′03″ E) was laid on the woodland 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. predominated 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 plantations 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 laid on a woodland plateau. Forest stands 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 thapsus L., Ajuga genevensis L. predominates. 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 woodland 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., Saussurea latifolia L., Ajuga genevensis L. predominates. 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 woodland 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. predominates. 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 Steallaria holostea L., Galiun aparine L., Glechoma hederacea L., Asarum europaeum L., Viola odorata L., Polygonum 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 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 Chelidonium majus L., Viola odorata L., Polygonum multiflorum (L.) All., Chaerophyllum temulum L., Alliaria petiolata (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), B2 (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 Dumont., Viola odorata L., Urtica dioica L., Chelidonium majus L., Alliaria petiolata (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.

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 (Na4P2O7) 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. Specific electrical resistivity of soil was studied by measuring current and voltage in pastes using a cuvette with a four-electrode sensor (Pozdniakov, 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 10⁻⁶ 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 obtained from 10 g saturated with atmospheric moisture (at 96–98% relative air humidity) over a 10% H2SO4 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 & Korchagina, 1986). 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% H2SO4 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 & Korchagina, 1986).

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

<table>
<thead>
<tr>
<th>Particle size, cm</th>
<th>Calcar Chernozem under steppe vegetation, %</th>
<th>Calcar Chernozem under R. pseudoacacia plantation, %</th>
<th>Calcar Chernozem under Q. robur plantation, %</th>
<th>Luvic Chernozem under natural forest vegetation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>154 ± 7.9</td>
<td>203 ± 9.8</td>
<td>190 ± 3.7</td>
<td>11.4 ± 4.0</td>
</tr>
<tr>
<td>20–40</td>
<td>145 ± 6.0</td>
<td>179 ± 10.0</td>
<td>180 ± 3.3</td>
<td>15.4 ± 7.9</td>
</tr>
<tr>
<td>Sand</td>
<td>114 ± 4.0</td>
<td>158 ± 9.7</td>
<td>176 ± 1.8</td>
<td>15.8 ± 2.5</td>
</tr>
<tr>
<td>60–80</td>
<td>92 ± 3.9</td>
<td>155 ± 8.4</td>
<td>155 ± 1.4</td>
<td>29.3 ± 2.8</td>
</tr>
<tr>
<td>80–100</td>
<td>94 ± 4.7</td>
<td>114 ± 6.5</td>
<td>117 ± 5.9</td>
<td>30.4 ± 13.5</td>
</tr>
<tr>
<td>0–20</td>
<td>58.7 ± 7.4</td>
<td>54.7 ± 6.9</td>
<td>61.8 ± 4.4</td>
<td>60.5 ± 9.8</td>
</tr>
<tr>
<td>20–40</td>
<td>57.5 ± 8.4</td>
<td>56.0 ± 11.5</td>
<td>61.8 ± 4.4</td>
<td>58.7 ± 7.4</td>
</tr>
<tr>
<td>Silt</td>
<td>59.4 ± 8.8</td>
<td>57.3 ± 13.3</td>
<td>60.8 ± 8.2</td>
<td>59.4 ± 8.8</td>
</tr>
<tr>
<td>60–80</td>
<td>60.5 ± 9.8</td>
<td>55.3 ± 8.4</td>
<td>62.7 ± 7.7</td>
<td>59.4 ± 8.8</td>
</tr>
<tr>
<td>80–100</td>
<td>59.4 ± 8.8</td>
<td>53.7 ± 7.2</td>
<td>61.8 ± 7.2</td>
<td>59.4 ± 8.8</td>
</tr>
<tr>
<td>Clay</td>
<td>25.9 ± 11.6</td>
<td>25.1 ± 6.6</td>
<td>17.7 ± 1.0</td>
<td>11.4 ± 4.0</td>
</tr>
<tr>
<td>20–40</td>
<td>28.0 ± 12.6</td>
<td>25.5 ± 7.4</td>
<td>20.2 ± 5.2</td>
<td>15.4 ± 7.9</td>
</tr>
<tr>
<td>40–60</td>
<td>29.3 ± 12.6</td>
<td>27.0 ± 7.2</td>
<td>21.7 ± 9.0</td>
<td>15.8 ± 2.5</td>
</tr>
<tr>
<td>60–80</td>
<td>30.4 ± 13.5</td>
<td>29.2 ± 4.9</td>
<td>21.8 ± 8.7</td>
<td>18.0 ± 3.3</td>
</tr>
<tr>
<td>80–100</td>
<td>31.2 ± 12.0</td>
<td>29.6 ± 6.9</td>
<td>22.4 ± 9.7</td>
<td>18.0 ± 3.3</td>
</tr>
</tbody>
</table>

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 in the upper 0–20 cm layer of ordinary chernozems the clay content is higher than in luvic chernozems.

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 clay 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.

**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 OriginLab 9.1 (OriginLab, 2013, USA). The results were tabulated as x ± SD (standard deviation). The differences between the values of 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).

**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 growth of artificial and natural forest vegetation contributes to an increase 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 0.5–0.50 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 the 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 (90%), 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 >10 mm (F = 11.18, P = 3.1·10^{-5}) and 5–7 mm (F = 5.73, P = 8.7·10^{-4}).

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 loisol (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 (25.3%). Ordinarily, chernozems under artificial forest plantations and luvic chernozems under natural 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 0–20 cm layer of ordinary chernozems under oak plantations (25.3%). Ordinarily, 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 0–20 cm layer of luvic chernozem (59.4%). The growth of artificial and natural forest vegetation 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 (26.4–26.5), 2–3 mm (28.6–28.7), 3–5 mm (26.4–26.5), and 5–7 mm (26.4–26.5), to the second – content of water-resistant fraction aggregates of the fraction >10 mm (F = 11.18, P = 3.1·10^{-5}) and 5–7 mm (F = 5.73, P = 8.7·10^{-4}).

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 the 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 oak plantations (30.8%). 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 (26.4–26.5), 2–3 mm (28.6–28.7), 3–5 mm (26.4–26.5), and 5–7 mm (26.4–26.5), to the second – content of water-resistant fraction aggregates of the fraction >10 mm (F = 11.18, P = 3.1·10^{-5}) and 5–7 mm (F = 5.73, P = 8.7·10^{-4}).
gates < 0.25–2 mm (S(1–2), S(0.5–1), N(0.5–1), S(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(1–5), N(1–5), 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)), (Q(1–5)). 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)

<table>
<thead>
<tr>
<th>Aggregate size, mm</th>
<th>Bulk density, g/cm³</th>
<th>Particle density, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.25</td>
<td>2.342 ± 0.034</td>
<td>1.296 ± 0.042</td>
</tr>
<tr>
<td>0.25–0.50</td>
<td>2.517 ± 0.029</td>
<td>1.454 ± 0.039</td>
</tr>
<tr>
<td>0.5–1.0</td>
<td>2.446 ± 0.035</td>
<td>1.342 ± 0.056</td>
</tr>
<tr>
<td>1.0–2</td>
<td>2.342 ± 0.034</td>
<td>1.296 ± 0.042</td>
</tr>
<tr>
<td>2–3</td>
<td>2.517 ± 0.029</td>
<td>1.454 ± 0.039</td>
</tr>
<tr>
<td>3–5</td>
<td>2.446 ± 0.035</td>
<td>1.342 ± 0.056</td>
</tr>
<tr>
<td>5–7</td>
<td>2.342 ± 0.034</td>
<td>1.296 ± 0.042</td>
</tr>
<tr>
<td>7–10</td>
<td>2.517 ± 0.029</td>
<td>1.454 ± 0.039</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>2.446 ± 0.035</td>
<td>1.342 ± 0.056</td>
</tr>
</tbody>
</table>

### Table 4

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Depth, cm</th>
<th>Bulk density, g/cm³</th>
<th>Particle density, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total porosity</td>
<td>0–20</td>
<td>4.1 ± 0.2</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td>Bulk density, g/cm³</td>
<td>0–20</td>
<td>1.2 ± 0.1</td>
<td>0.7 ± 0.05</td>
</tr>
<tr>
<td>Particle density, g/cm³</td>
<td>0–20</td>
<td>0.5 ± 0.05</td>
<td>0.3 ± 0.03</td>
</tr>
</tbody>
</table>

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•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.

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the minimum – in the 0–20 cm layer of luvic chernozems (14.6).

...and oak plantations, the content of sand and silt increased compared to ordinary chernozems under steppe vegetation. The growth of 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 (Ju 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 > 1, 0.75–1, 0.5–0.75 and 0.25–0.5 mm and a decrease in the content of aggregates of fractions 0.25–0.5 and 0.125–0.25 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 soil aggregates. The growth of forest plantations and natural forest vegetation on chernozems led to an increase in the content of water-resistant aggregates of fractions > 3, 2.5–3, 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 under 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

### Table 5

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Depth, cm</th>
<th>Calcareous Chernozem under steppe vegetation</th>
<th>Calcareous Chernozem under R. pseudoacacia plantation</th>
<th>Calcareous Chernozem under Q. robur plantation</th>
<th>Luvic Chernozem under natural forest vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–20</td>
<td>32.1 ± 1.12</td>
<td>33.3 ± 1.47</td>
<td>30.7 ± 1.47</td>
<td>32.5 ± 1.56</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>27.4 ± 0.50</td>
<td>32.2 ± 1.60</td>
<td>30.6 ± 1.47</td>
<td>37.9 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>40–60</td>
<td>27.1 ± 0.45</td>
<td>31.5 ± 2.50</td>
<td>28.6 ± 2.55</td>
<td>35.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>60–80</td>
<td>26.1 ± 1.74</td>
<td>31.3 ± 3.50</td>
<td>27.9 ± 3.7</td>
<td>33.7 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>80–100</td>
<td>25.1 ± 5.50</td>
<td>32.5 ± 6.00</td>
<td>28.3 ± 4.5</td>
<td>32.8 ± 1.0</td>
</tr>
</tbody>
</table>

**Note:** see Table 1.

### Table 6

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Depth, cm</th>
<th>Calcareous Chernozem under steppe vegetation</th>
<th>Calcareous Chernozem under R. pseudoacacia plantation</th>
<th>Calcareous Chernozem under Q. robur plantation</th>
<th>Luvic Chernozem under natural forest vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–20</td>
<td>73.6 ± 15.8</td>
<td>81.2 ± 22.8</td>
<td>82.7 ± 21.4</td>
<td>106.3 ± 7.3</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>56.2 ± 18.5</td>
<td>63.9 ± 26.2</td>
<td>68.1 ± 22.9</td>
<td>84.6 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>60–80</td>
<td>59.0 ± 13.8</td>
<td>64.9 ± 22.7</td>
<td>56.8 ± 25.5</td>
<td>65.3 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>80–100</td>
<td>53.2 ± 9.4</td>
<td>73.6 ± 29.1</td>
<td>62.7 ± 21.1</td>
<td>69.5 ± 8.2</td>
</tr>
</tbody>
</table>

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

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).

...and oak permeability, 40–60 | 53.4 ± 18.7 | 62.2 ± 20.3 | 51.9 ± 18.8 | 75.0 ± 2.2 |

...and oak permeability, 40–60 | 53.4 ± 18.7 | 62.2 ± 20.3 | 51.9 ± 18.8 | 75.0 ± 2.2 |

...and oak permeability, 40–60 | 53.4 ± 18.7 | 62.2 ± 20.3 | 51.9 ± 18.8 | 75.0 ± 2.2 |

...and oak permeability, 40–60 | 53.4 ± 18.7 | 62.2 ± 20.3 | 51.9 ± 18.8 | 75.0 ± 2.2 |
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 chernozems (Tsverkova & Saranenko, 2007, 2010; Saranenko, 2011; Tsverkova 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), Parizzi & Fatchi (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 plantations was manifested in an increase in the electrical resistivity of luvic 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. The research was carried out at the authors’ own expense.

The authors declare no conflict of interest.

References


