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Changes in selected properties of Calcic Chernozem due to cultivation of *Robinia pseudoacacia* and *Quercus robur*

Vadym Gorban*, Artem Huslystyi

Department of Geobotany, Soil Science and Ecology, Oles Honchar Dnipro
National University, Gagarin ave. 72, Dnipro, 49010, Ukraine

Abstract

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The results of a comprehensive study on the particle size distribution, soil organic matter (SOM) content, and plant-available water in Calcic Chernozem are presented, along with the impact of *Robinia pseudoacacia* L. and *Quercus robur* L. plantations on these indicators. The study revealed that Calcic Chernozem under steppe vegetation and *Q. robur* plantation exhibited a silty clay loam texture. However, under the influence of *R. pseudoacacia* plantation, the chernozem's texture transformed into loam. The planting of *R. pseudoacacia* resulted in a noticeable decrease in SOM content, while the growth of *Q. robur* plantations led to an increase in SOM content. Furthermore, both *R. pseudoacacia* and *Q. robur* plantations contributed to an increased content of plant-available water in the 0–20 cm layer of chernozem. These findings highlight the more pronounced effect of *R. pseudoacacia plantation* on the particle size distribution, SOM content, and plant-available water in Calcic Chernozem compared to *Q. robur* plantation.

Keywords

forest plantings, organic matter, soil texture, steppe soils, water content

Introduction

Calcic Chernozem occupies the largest area within the steppe zone of Ukraine. Similar to many other soils worldwide, this soil type exhibits various degradation processes (Labaz et al., 2022). The main causes of soil degradation are anthropogenic impact and global climate change (Roy et al., 2022). One significant consequence of these degradation processes is a drastic decrease in soil fertility, primarily attributed to declining organic matter content (He et al., 2023). This fully applies to Calcic Chernozem.

Chernozems are known for their higher fertility potential when compared to other soil types (Han and Zou, 2022). The main limiting factor for steppe soil fertility is insufficient moisture (Belova and Travleev, 1999). Soil water-holding capacity is a complex characteristic, which is largely determined by the peculiarities of the particle size distribution and SOM content (Lal, 2020). These properties play a significant role in determining the soil's potential fertility (Paul et al., 2023; Qi et al., 2018).

Soil particle size distribution is a basic soil physical property, that strongly influences soil structure, water movement, fertility development, porosity condition and soil-formation process (Li et al., 2022; Sha et al., 2022). Wang et al. (2019) found a significant effect of particle size distribution on the water retention properties of black soil itself. A negative relationship was observed between soil field capacity and sand particle content of soil, while silt and clay particle content showed a significant increase in soil field capacity. Loamy soil has the largest water holding capacity, followed by sandy loam, while sandy soil had the lowest water-holding capacity (Wang et al., 2019).

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*Corresponding author:
e-mail: gorvadym@gmail.com

The particle size distribution is an important background for the identification of influence of soil organic matter (SOM) content on water-retaining capacity. Studies show that the addition of organic matter in the form of biochar to sandy soil increases its water-holding capacity, while silt loams and clay soils show minimal changes (ZHANG et al., 2021). Increasing the SOM content in the soil increases both soil water retention and plant available water capacity (LAL, 2020). The magnitude of increase in plant available water capacity may vary depending on soil texture and the initial SOM content (ABDALLAH et al., 2021). Increasing organic matter content to a certain degree can reduce evaporation and infiltration of soil moisture, thereby improving water use efficiency (DING et al., 2013). However, some scientists argue that the impact of SOM on soil water content is relatively small (MINASNY and MCBRATNEY, 2018).

Soil water-holding capacity, a factor governing soil functioning in ecosystems, can be significantly altered by the accelerated climate change and vegetation degradation (LIN et al., 2023). The most effective soil management approach for climate change mitigation should focus on promoting vegetation growth while maximizing soil organic matter content and water retention (CERTINI and SCALENGHE, 2023).

Studies have demonstrated that one of the most effective ways to conserve soil and restore soil fertility in the steppe zone is the establishment of a functional system of protective forest plantations (CHATTERJEE et al., 2018; W. WU et al., 2023). These plantations have a complex positive impact on soils and the environment (GRITSAN et al., 2019; WANG et al., 2022). *Robinia pseudoacacia* and *Quercus robur* plantations occupy the largest areas in the steppe zone of Ukraine. These plantations exhibit diverse effects on the properties of Calcic Chernozem (GORBAN et al., 2020). There is a need to conduct more detailed studies of the influence of forest plantations on steppe soils and their individual properties. Such research will provide a better understanding of the specific environmental characteristics amidst global climate change.

The objective of our study is to investigate the impact of *R. pseudoacacia* and *Q. robur* plantations on the particle size distribution, soil organic matter (SOM) content, and plant-available water in Calcic Chernozem within the steppe zone of Ukraine.

Materials and methods

Site characteristics

Studies of particle size distribution, content of organic matter and plant available water of Calcic Chernozem were carried out on the territory of the National Park "Samarskiy Bir" located in the southeastern part of the steppe zone of Ukraine (Novomoskovskiy district, Dnipropetrovsk oblast, Ukraine) (Fig. 1).

Detailed descriptions of sample sites and soil sections can be found in the studies of YAKOVENKO (2017) and GORBAN et al. (2020, 2021). Below we provide a brief description of the objects under study based on the aforementioned references.

Site 1 was located within the virgin steppe land of a watershed plateau (South-Eastern part of the Andriivka village, 48°45'36.9"N, 35°27'40.5"E). Herbaceous vegetative cover was closed, consisted 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. Groundwater depth was approximately 40 m. The soil profile was described as follows: A_1 (0–7 cm), A_2 (7–26 cm), Bk_1 (26–42 cm), Bk_2 (42–57 cm), Ck (57–120 cm+). The soil was identified as Calcic Chernozem.

Site 2 was located on the watershed plateau

Fig. 1. Location of the sites in the territory of the National Park "Samarskiy Bir" (Novomoskovskiy district, Dnipropetrovsk oblast, Ukraine).

westward of Vsesviatske village (48°45’27.6”N, 35°29’33.4”E). The groundwater depth was approximately 40 m below the ground surface. The forest stand consisted of *Robinia pseudoacacia* L. trees approximately 60 years old, with and average height of 4–6 m and a stem diameter of 10–12 cm. The stand had a canopy density of 0.7. The tree planting was arranged in lines with a drilling distance of 0.5 meters and a distance of 1 meter between rows. *Elytrigia repens* L., *Poa angustifolia* L., *Chelidonium majus* L. predominated in the herbaceous cover, with a total coverage of about 60–70%. The soil profile was described as follows: A (0–14 cm), B (14–34 cm), Bk (34–56 cm), Ck (56–120 cm+) and it was identified as Calcic Chernozem.

Site 3 (48°45’27.0”N, 35°30’09.5”E) was situated on a watershed plateau adjacent to Site 2. The forest stand at this site consisted of *Quercus robur* L. trees, also approximately 60 years old with an average tree height of 7–9 m and stem diameter of 10–14 cm. The stand had a canopy density of 0.9. Similar to Site 2, the tree planting was arranged in lines, but in this case, rows of oak trees were alternated with rows of shrubs such as *Acer tataricum* L. and occasionally *Euonymus europaeus* L. The distance between rows was 0.75 m and the drilling distance was 1.5 m. The dominant herbaceous cover included *Elytrigia repens* L., *Verbascum lychnitis* L., *Salvia verticillata* L., *Ajuga genevensis* L. covering approximately 20–25% of the area. The soil profile description was as follows: A_1 (0–9 cm), A_2 (9–42 cm), Bk_1 (42–62 cm), Bk_2 (62–81 cm), Ck (81–120 cm+), with the soil type identified as Calcic Chernozem.

Sample procedures

Approximately 1 kg of composite soil sample was collected from each of the three sites during the summer of 2017. The samples were obtained from the middle of each 20-centimeter layer, to a depth of 100 cm. The soil samples were subsequently used for laboratory analysis to determine of their particle size distribution, content of organic matter and plant available water.

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 IUSS Working Group WRB 2015. Air-dried soil samples were used for laboratory studies.

The particle size distribution of the soil was determined by the pipette method (Carter and Gregorich, 2008), with a 4% sodium pyrophosphate solution ($Na_4P_2O_7$) used as a dispersant.

The organic matter content in the soil was determined using the oxidimetric method. Soil organic matter was oxidized by a solution of potassium dichromate ($K_2Cr_2O_7$) at a temperature of 140–150 °C, followed by quantitative determination of portion unreacted with Mohr’s salt ($(NH_4)_2SO_4 \cdot FeSO_4 \cdot 6H_2O$) (Carter and Gregorich, 2008).

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. 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 and 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 weighting 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 and Korchahina, 1986).

Statistical analysis

The data obtained were analyzed using Statistica 6.0 (StatSoft Inc., 2012, 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).

Results and discussion

Effect of *R. pseudoacacia* and *Q. robur* plantations on particle size distribution of Calcic Chernozem

Soil particle size composition is one of the basic physical properties of soil, that influences changes in soil nutrients and moisture (Lou et al., 2022), making its study an important step in any soil ecological study.

The research revealed that the content of sand decreases with depth in the profile of the studied chernozems. However, under black locust plantation an increase in content of sand was observed in the layers of 60–80 and 80–100 cm compared to the 40–60 cm layer. The lowest sand content (21.37%) was found in the 0–20 cm layer of the chernozem under steppe vegetation, while the highest content (31.24%) was observed in the chernozem under *R. pseudoacacia* plantation (Table 1). The sand content in this layer differed significantly between the chernozem under steppe vegetation and oak plantation as well as chernozem under black locust plantation. The minimum sand content in the layers of 20–40, 40–60, 60–80 and 80–100 cm was also found in the chernozem under steppe vegetation while the maximum content was observed in the chernozem under *R. pseudoacacia* plantation. Significant differences in sand content were observed in these layers for all three studied soils.

The content of silt in the profiles of the studied chernozems increases with depth. The difference between the minimum content in the 0–20 cm layer and the maxi

Table 1. Particle size distribution of Calcic Chernozem (x ± SD), n = 3.

Depth (cm)	Calcic Chernozem under steppe vegetation	Calcic Chernozem under *R. pseudoacacia* plantation	Calcic Chernozem under *Q. robur* plantation
Sand (%)			
0–20	21.37 ± 1.18^{a}	31.24 ± 1.02^{b}	23.41 ± 0.53^{a}
20–40	17.56 ± 0.95^{a}	28.34 ± 0.96^{b}	21.78 ± 0.48^{c}
40–60	10.44 ± 0.47^{a}	26.90 ± 0.94^{b}	18.90 ± 0.65^{c}
60–80	5.48 ± 0.53^{a}	28.56 ± 1.06^{b}	16.27 ± 1.04^{c}
80–100	6.04 ± 0.71^{a}	30.44 ± 0.50^{b}	14.17 ± 0.57^{c}
Silt (%)			
0–20	53.07 ± 0.63^{a}	43.68 ± 0.48^{b}	46.84 ± 0.29^{c}
20–40	52.04 ± 0.28^{a}	42.87 ± 0.52^{b}	46.97 ± 0.42^{c}
40–60	53.44 ± 0.50^{a}	43.22 ± 0.27^{b}	48.12 ± 0.49^{c}
60–80	54.28 ± 0.68^{a}	45.67 ± 0.61^{b}	49.85 ± 0.51^{c}
80–100	55.84 ± 0.44^{a}	46.96 ± 1.01^{b}	50.24 ± 0.55^{c}
Clay (%)			
0–20	25.56 ± 0.86^{a}	25.08 ± 0.38^{a}	29.75 ± 0.42^{b}
20–40	30.47 ± 1.05^{a}	28.79 ± 0.44^{b}	31.25 ± 0.26^{b}
40–60	36.17 ± 0.80^{a}	29.89 ± 0.89^{b}	32.99 ± 0.79^{c}
60–80	40.24 ± 1.08^{a}	25.77 ± 0.49^{b}	33.88 ± 1.02^{c}
80–100	38.12 ± 0.80^{a}	22.60 ± 0.31^{b}	35.59 ± 1.50^{a}

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 $p < 0.05$.

mum content in the 80–100 cm layer was small, indicating a uniform distribution of silt in the profiles of the studied chernozems. The highest silt content (53.07%) was found in the 0–20 cm layer of the chernozem under steppe vegetation, while the lowest content (43.68%) was observed in the chernozem under black locust plantation. All the studied chernozems showed significant differences in terms of silt content.

In the profiles of chernozems under steppe vegetation and under oak plantation, an increase in clay content with depth was observed. The maximum clay content in the chernozem under *R. pseudoacacia* plantation was found in the 40–60 cm layer, while a decrease in clay content was observed in the 60–80 and 80–100 cm layers. The minimum clay content (25.08%) was indicated in the 0–20 cm layer in the chernozem under black locust plantation, while the maximum amount (29.75%) was found in the chernozem under oak plantation. The minimum clay content in the 20–40 cm layer was observed in the chernozem under the black locust plantation, while the maximum was found in the chernozem under the oak plantation. The influence of tree plantations led to a significant change in clay content in the chernozem. In the 40–60 and 60–80 cm layers, the minimum clay content was observed in the chernozem under black locust plantation, while the maximum was found in the chernozem under steppe vegetation. Significant differences in clay content were found among all three studied soils in these layers. In the 80–100 cm layer, the minimum clay content (22.60%) was typical for the chernozem under black locust plantation, and the maximum (38.12%) was found in chernozem under steppe vegetation. Significant differences in clay content were observed between the chernozems under steppe vegetation and *Q. robur* plantation.

The results of the study indicated that silt was the predominant particle size fraction in the studied soils. These findings are consistent with the conclusions of our previous study (Gorban, 2021).

An analysis of particle size composition showed that the growth of black locust and oak plantings on Calcic Chernozem led to an increase in sand content and a decrease in silt and clay content. The impact of *R. pseudoacacia* plantation resulted in a more significant change in the particle size composition of the chernozem compared to *Q. robur* plantation. Li et al. (2022) found that the growth of *R. pseudoacacia* led to a decrease in sand content in black soil, while Su et al. (2022) noted that the impact of *Q. robur* planting resulted in an increase in silt and clay content in chernozem. The inconsistency of our results with the findings these authors may be attributed to differences in the properties and genesis of the studied soils.

Influence of *R. pseudoacacia and Q. robur* plantations on content of SOM in Calcic Chernozem

Soil organic carbon and soil organic matter have significant effects on soil physical, chemical and biological properties. They play a crucial role in regulating the balance between soil water and air, increasing soil water holding capacity and improving plant productivity (Wang et al., 2023). Therefore, studying characteristics of the organic component of the soil is an essential step in any ecological research.

The profiles of all studied chernozems were characterized by the highest content of SOM in the 0–20 cm layer. A decrease in SOM content with increasing depth was observed. The patterns of SOM distribution in the chernozem profile are typical of the steppe soil formation type (Belova and Travleev, 1999). The highest content of SOM (3.65%) was found in the 0–20 cm layer of the chernozem under the oak plantation, while the lowest content (2.34%) was found in the chernozem under the black locust

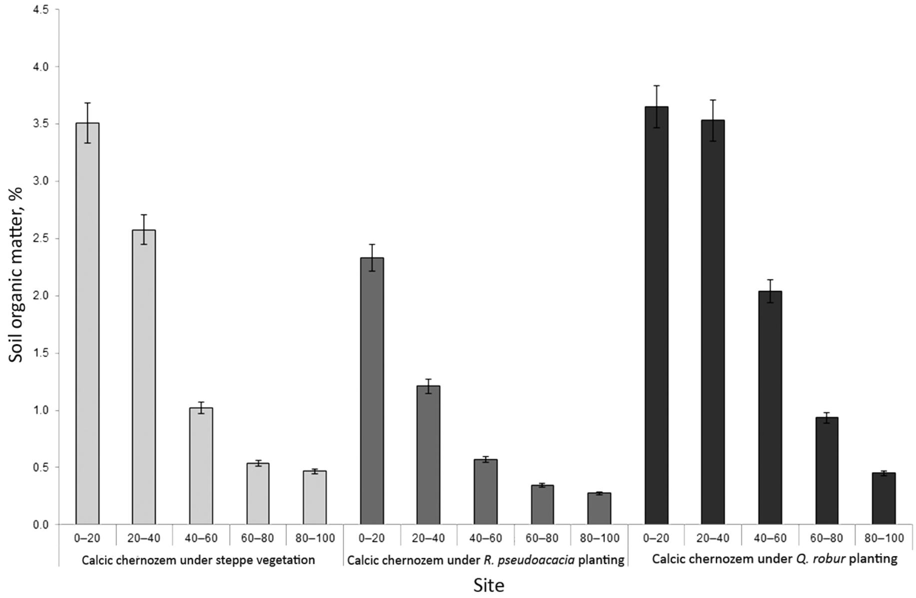

Fig. 2. Content of soil organic matter of Calcic Chernozem.

plantation (Fig. 2). The content of SOM in the chernozem under steppe vegetation and *Q. robur* planting significantly differs from the content of SOM in the chernozem under *R. pseudoacacia* planting. In the 20–40, 40–60 and 60–80 cm layers, the highest content of SOM was observed in the chernozem under oak plantation, while the lowest content was found in the chernozem under black locust plantation. Significant differences in SOM content were observed in these layers across all three studied soils. In the 80–100 cm layer, the highest content of SOM (0.47%) was found in the chernozem under steppe vegetation, while the lowest content (0.28%) was found in the chernozem under black locust plantation. The content of SOM in this layer in the chernozem under steppe vegetation and *Q. robur* planting significantly differed from the content of SOM in the chernozem under *R. pseudoacacia* planting. The study results showed that the growth of black locust plantations on chernozem led to a decrease in SOM content, while the growth of oak plantations led to an increase in SOM content. This observation may be attributed to the specific functioning of bacterial community composition in these forest types, which influence the formation and accumulation of SOM in the soil (Li et al., 2021).

Influence of *R. pseudoacacia and Q. robur* plantations on plant available water in Calcic Chernozem

Soil hydrological properties play a key role in soil hydrological processes (Qiu et al., 2022). However, the comprehensive effects of different types of vegetation restoration on soil properties, including hydrological ones, remain unclear (H. Wu et al., 2023).

Plant available water is defined as the difference between the water-holding capacity and the water content at the wilting point (de Melo et al., 2023). Therefore, the analysis initially focused on determining the values of water-holding capacity and water content at the wilting point for the studied chernozems.

Table 2. Water-holding capacity and water content at the wilting point of Calcic Chernozem (x ± SD), n = 3.

Depth (cm)	Calcic Chernozem under steppe vegetation	Calcic Chernozem under *R. pseudoacacia* plantation	Calcic Chernozem under *Q. robur* plantation
Water-holding capacity (%)			
0–20	47.12 ± 1.47^{a}	51.23 ± 1.91^{a}	49.83 ± 0.37^{a}
20–40	48.52 ± 1.38^{a}	48.80 ± 0.42^{a}	47.52 ± 0.67^{a}
40–60	49.44 ± 1.62^{a}	47.35 ± 0.90^{b}	45.13 ± 0.65^{a}
60–80	48.50 ± 0.73^{a}	47.45 ± 0.47^{a}	44.81 ± 0.91^{b}
80–100	44.12 ± 0.90^{a}	44.20 ± 0.20^{a}	44.55 ± 0.48^{a}
Water content at wilting point (%)			
0–20	14.70 ± 0.70^{a}	13.05 ± 0.75^{a}	14.16 ± 0.28^{a}
20–40	14.89 ± 0.51^{a}	11.32 ± 0.75^{b}	14.06 ± 0.39^{a}
40–60	15.01 ± 0.88^{a}	10.16 ± 0.47^{b}	13.88 ± 0.29^{a}
60–80	14.04 ± 0.59^{a}	8.09 ± 0.43^{b}	12.77 ± 0.38^{a}
80–100	12.35 ± 0.74^{a}	7.88 ± 0.39^{b}	11.70 ± 0.36^{a}

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 $p < 0.05$.

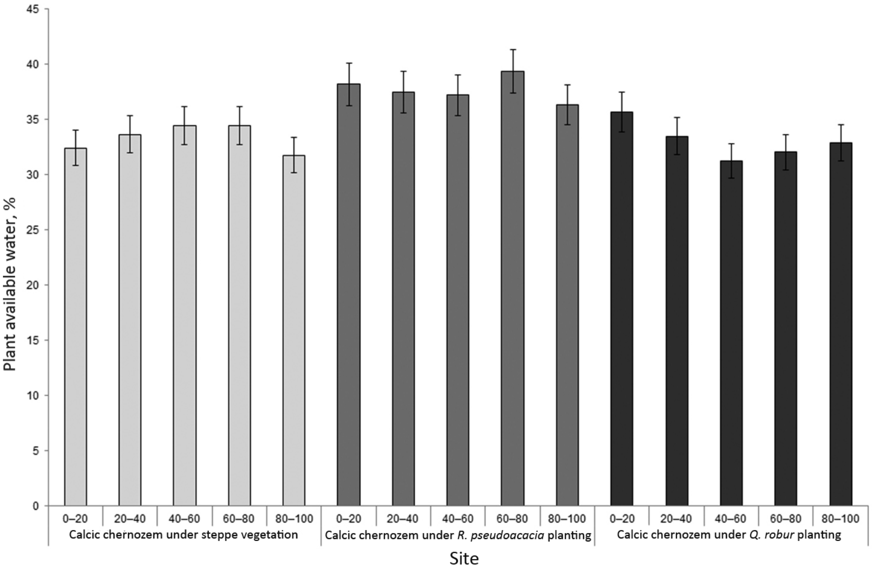

Fig. 3. Plant available water of Calcic Chernozem.

The maximum water-holding capacity in the profile in the chernozem under steppe vegetation was found in the layer of 40–60 cm, while the minimum was observed in the layer of 80–100 cm. In the profiles of chernozem under *R. pseudoacacia* and *Q. robur* plantations the maximum water-holding capacity was indicated in the layer of 0–20 cm. A decrease in water-holding capacity with increasing depth was observed. Specifically, the chernozem under black locust plantation exhibited the highest water-holding capacity (51.23%) in the layer of 0–20 cm, while the chernozem under steppe vegetation had the lowest (47.12%) (Table 2). In the layer of 20–40 cm, the chernozem under *R. pseudoacacia* plantation had the maximum water-holding capacity, whereas the chernozem under *Q. robur* plantation had the minimum. In the 40–60 and 60–80 cm layers, the chernozem under steppe vegetation had the highest water-holding capacity while the chernozem under oak plantation had the lowest. The differences in water-holding capacity among the studied soils were not significant in the layer of 80–100 cm.

In the profile of chernozem under steppe vegetation, the maximum water content at the wilting point (15.01%) was found in the 40–60 cm layer. A decrease of water content at the wilting point with increasing depth was observed. In the profiles of chernozem under *R. pseudoacacia* and *Q. robur* plantations, the maximum water content at the wilting point was found in the layer of 0–20 cm. The chernozem under steppe vegetation exhibited the highest values of water content at the wilting point, while the chernozem under black locust plantation had the lowest values for all the studied layers in the soil profiles. In the layers of 20–40, 40–60, 60–80 and 80–100 cm, the chernozem under steppe vegetation and *Q. robur* plantation significantly differed in water content at the wilting point from the chernozem under *R. pseudoacacia* plantation.

The layer of 80–100 cm in the profile of chernozem under steppe vegetation exhibited the minimum of plant available water, while this indicator increased from the layer of 0–20 cm to the layer of 60–80 cm (Fig. 3). In the profile of chernozem under black locust plantation, the maximum plant available water was observed in the layer of 60–80 cm, and the minimum was found in the layer of 80–100 cm. Similarly, in the profile of the chernozem under the *Q. robur* plantation, the maximum plant available water was found in the layer of 0–20 cm. An analysis of plant available water revealed that the chernozem under the *R. pseudoacacia* plantation exhibited the highest values. This soil significantly differed in plant available water from the chernozem under steppe vegetation and under oak plantation. The minimum plant available water (32.42%) was found in the chernozem under steppe vegetation in the layer of 0–20 cm. In the layers of 20–40, 40–60 and 60–80 cm, the minimum plant available water was observed in the chernozem under oak plantation. Furthermore, the minimum plant available water (31.77%) in the layer of 80–100 cm was indicated for the chernozem under steppe vegetation.

The results of the study showed that the growth of *R. pseudoacacia* plantation on Calcic Chernozem significantly increased plant available water compared to chernozem under steppe vegetation and *Q. robur* plantation. This finding aligns with the work of De Marco et al. (2023), who also observed an increase in water-holding capacity and plant available water in the soil as a result of acacia growth.

Conclusions

Calcic Chernozem under the steppe vegetation is classified as silty clay loam. The growth of *R. pseudoacacia* has an influence on the chernozem, changing it to loamy texture due to an increase in sand content. On the other hand, the effect of *Q. robur* plantation does not result in a change in the particle size distribution of the chernozem. The maximum content of SOM was consistently found in the 0–20 cm layer of all studied chernozems. The growth of black locust plantation on the chernozem leads to a decrease in SOM content, while the growth of oak plantation leads to an increase in SOM content. Both *R. pseudoacacia* and

Q. robur plantations contribute to an increase in the water-holding capacity of the chernozem in 0–20 cm layer. In the chernozem under the influence of black locust and oak plantations, a decrease in water content at wilting point along the soil profile was observed. Furthermore, the effect of black locust and oak plantations leads to an increase in the plant available water in the 0–20 cm layer. The growth of *R. pseudoacacia* had a more pronounced effect on the particle size distribution, SOM content and plant available water of chernozem compared to *Q. robur* plantation.

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