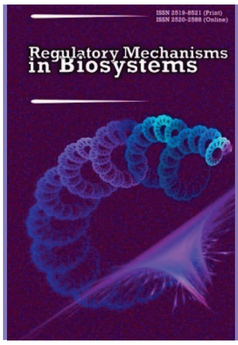

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Mechanisms of influence of forest ecosystems on the aggregate composition and water stability of soil aggregates in the semi-arid area of southeast Ukraine

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Modern processes of climate change are accompanied by a number of negative factors, which include aridization, desertification, soil degradation and erosion. The research was were carried out on the territory that is the southern border of the distribution of the late glacial phase of the Dnieper glaciation (Middle Pleistocene, 100–230 thousand years ago). The influence of forest ecosystems on the aggregate composition and water stability of soil aggregates, the features of which determine the protection of soils from erosion and other degradation processes in semiarid conditions, was assessed. It has been established that luvic chernozems of forest ecosystems are characterized by an increased content of aggregates of fractions 2–3, 1–2 and 0.5–1.0 mm, as well as water-stable aggregates of fractions > 5, 0.5–1.0 and 0.25–0.5 mm in the 0–20 cm layer compared to ordinary chernozems of steppe ecosystems. The content of soil organic matter is a determining factor on which the aggregate composition and content of water-stable aggregates in luvic chernozems of forest ecosystems depends. The existence of close direct relationships has been established between the content of soil organic matter and the content of aggregates of the 0.5–1.0 mm fraction, as well as between the content of soil organic matter and the content of water-stable aggregates of fractions 3–5, 2–3 and 1–2 mm in chernozems of steppe and forest ecosystems. The existence of close direct relationships between the sand content and the content of water-stable aggregates of fractions 3–5 and 2–3 mm was revealed. The established increase in the content of soil organic matter and sand in luvic chernozems of forest ecosystems compared to ordinary chernozems of steppe ecosystems is the reason for the improvement in the aggregate composition and the increase in the content of water-stable aggregates. This is a key aspect of increasing the resistance of soils in forest ecosystems to various negative factors, such as desertification, degradation, wind and water soil erosion.

Keywords: ordinary chernozem; luvic chernozem; soil organic matter; sand; silt; clay; slopes of northern and southern exposures.

Introduction

The aggregate composition of soils is an important indicator of their resistance to wind erosion (Le Bissonnais et al., 2017; Zheng et al., 2023), and the water resistance of aggregates is an important indicator of resistance to water erosion (Liang et al., 2023). The aggregate composition and content of water-resistant aggregates in the soil depends on many factors – particle size distribution (Gao & Yang, 2023), characteristics of soil organic matter (Li et al., 2017; Yang et al., 2023), type of vegetation, ecosystems and land use (Dou et al., 2020; Yang et al., 2024).

In the semi-arid steppe zone of Ukraine, natural forest ecosystems occur in small areas that are confined to river valleys, steep sides of river banks, gullies and ravines of the watersheds of the eroded right-bank slopes of the Dnieper River and its tributaries (Belova & Travleev, 1999). Until recently, researchers expressed doubts that in steppe conditions, full-fledged chernozem soils could form under natural forest vegetation (Travleev, 1996). The results of complex studies carried out by Belova & Travleev (1999), Yakovenko (2017), Bozhko & Bilova (2020), Ponomarenko et al. (2022), Yakovenko et al. (2024) confirm the fact of the formation of chernozem soils under natural forest vegetation in the steppe zone of Ukraine.

European researchers also began to pay considerable attention to this issue. A review paper by Eckmeier et al. (2007) argues that the formation of Central European chernozems dates back to the early Holocene, and also provide evidence for the possibility of the formation of chernozems under woody vegetation. Vysloužilová et al. (2014) in the conditions of Central Europe, discovered chernozems in areas that, due to climatic factors, do not correspond to steppe conditions. This gave rise to the assumption that the preservation of chernozems under forest vegetation is associated with the high stability of their organic matter. Thiele-Bruhn et al. (2014) note that the formation of chernozems in Central Europe is a relict process and is determined not only by the conditions of the steppe ecosystem, but also depends on the properties of the original substrate, especially on the content of clay and carbonates, the supply of secondary carbonates, and anthropogenic use of the soil. Lasota et al. (2019) found formed chernozems under woody vegetation in Poland. Łabaz et al. (2019) provide evidence of the fact that the chernozem soils of Southwestern Poland, which are characterized by a thick mollic horizon, rich in humus, dark-colored, structural and saturated with base cations, were formed not only in pronounced steppe conditions under zonal vegetation. Strouhalova et al. (2019) as a result of a paleoecological study of 23 chernozem sites in Central Europe found that most of the studied chernozems have a meadow past, but some of them also existed under forest. Labaz et al. (2022) found chernozems in the moderately humid climate of southeastern Poland under mixed broad-leaved forests. Kobza & Pálka (2022) note that in Slovakia, soils with characteristics characteristic of chernozems are found not only in steppe conditions, but also under forest vegetation. The main factor in the steppe that limits the growth and development of forest vegetation is the amount of moisture (Belova & Travleev, 1999). The best conditions, from this point of view, are river valleys, as well as the middle and lower parts of the slopes, which differ from each other depending on the exposure, with the most contrasting differences being characterized by the northern and southern exposures (Belova & Travleev, 1999; Bozhko & Bilova, 2020). Ding et al. (2024) found that soils on the northern slope have better physical properties than those on the southern slope. Soil nutrient content is largely determined by the location of the study site (top, middle, or bottom) and slope aspect (Gou et al., 2015). The works of Guo et al. (2021), Chen et al. (2023) noted that slope features have a significant impact on soil properties and erodibility. Wang et al. (2021) found that plant litter and root density, soil bulk density, soil texture, and organic matter content depended on the position and appearance of the landscape. In some cases, the influence of the land use system has a more pronounced impact on the properties of the soil compared to the features of its topographical attributes (Bamutaze et al., 2021). The purpose of our work is to assess the influence of forest ecosystems on the aggregate composition and water stability of soil aggregates, as well as their dependence on the content of soil organic matter and granulometric composition in the semiarid conditions of southeastern Ukraine.

Materials and methods

Study area. Figure 1 shows the location of the study area in Dnipropetrovsk region, which is located in the steppe zone of Ukraine.

Site 1 (48°47'14.76"N 35°27'10.25"E) located at the top of the slope (aspect N). Herbaceous vegetative cover was closed, consists of *Poa angustifolia* L., *Elytrigia repens* (L.) Nevski, *Achillea millefolium* L., *Salvia nemorosa* L., *Artemisia absinthium* L., *Galium aparine* L., *Viola odorata* L., *Lathyrus tuberosus* L., *Convolvus arvensis* L. and other herbaceous plant species. Soil profile description: Ak1 (0–8 cm), Ak2 (8–23 cm), Bk1 (23–51 cm), Bk2 (51–80 cm), Ck (80–120 cm). The soil is a Calcic Chernozem.

Site 2 (48°47'14.82"N 35°27'16.10"E) located at the top of the slope (aspect S). Herbaceous vegetative cover was closed, consists of *Festuca valesiaca* Schleich. ex Gaudin, *Poa angustifolia* L., *Elytrigia repens* (L.) Nevski, *Poa nemoralis* L., *Lathyrus tuberosus* L., *Achillea millefolium* L., *Euphorbia vigrata* Waldst. et Kit., *Thymus marschallianus* Willd., *Linum hirsutum* L., *Agrimonia eupatoria* L., *Salvia nemorosa* L. and other herbaceous plant species. Soil profile description: A1 (0–6 cm), A2 (6–27 cm), Bk (27–40 cm), Ck (40–120 cm). The soil is a Calcic Chernozem.

Site 3 (48°47'18.65"N 35°27'19.83"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 4 (48°47'20.79"N 35°27'23.50"E) was located on the middle ravine slope (aspect S). Natural forest was primarily formed by *Fraxinus exelsior* L., *Acer campestre* L., *Ulmus minor* Mill., *Tilia cordata* Mill., *Acer platanoides* L. Herbaceous cover was predominantly composed of *Glechoma hederacea* L., *Viola odorata* L., *Chelidonium majus* L., *Galium aparine* L., *Anthriscus sylvestris* (L.) Hoffm., *Geum urbanum* L., *Asarum europaeum* L., *Trifolium medium* L., *Aristolochia clematitis* L., *Potentilla argentea* L. Soil profile description: Ah1 (0–9 cm), Ah2 (9–46 cm), Ah3 (46–88 cm), Bt1 (88–138 cm), Bt2 (138–160 cm), Ck (160–187 cm). The soil is a Luvic Chernozem.

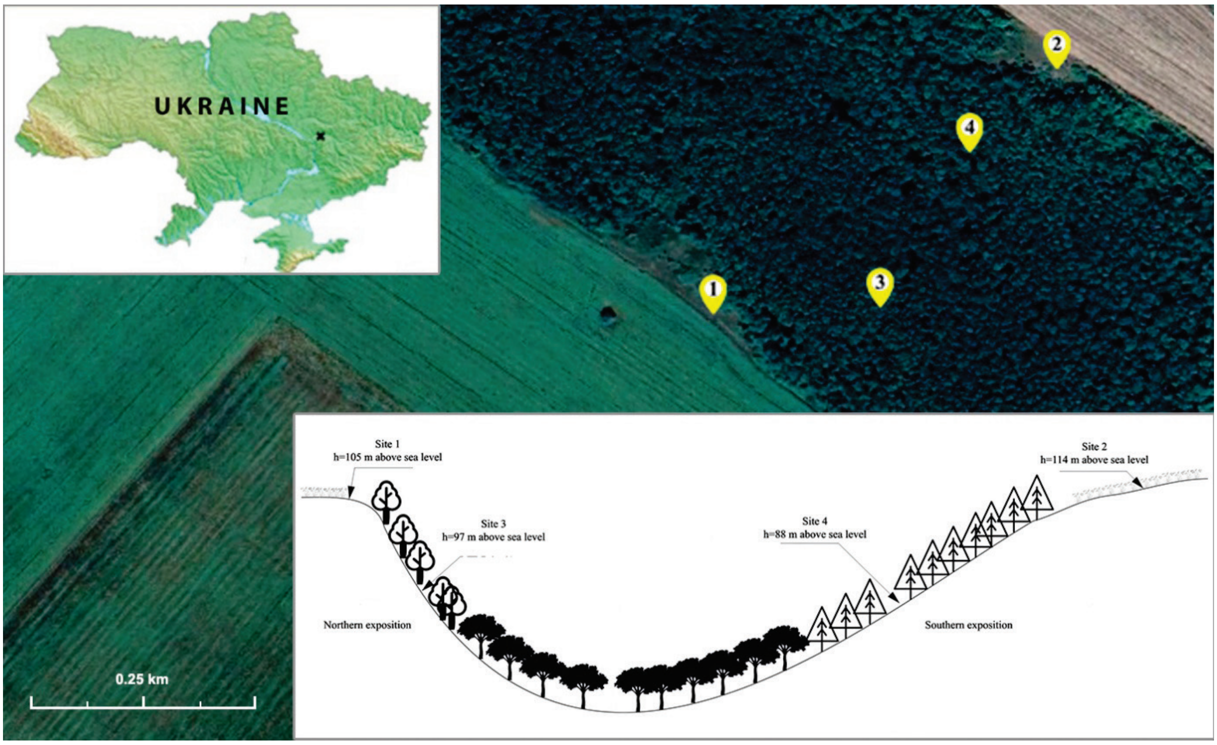

Fig. 1. Location of the sites (Dnipropetrovsk region, Ukraine): *1* – site 1 (ordinary chernozem, northern exposure); *2* – site 2 (ordinary chernozem, southern exposure); *3* – site 3 (luvic chernozem, northern exposure); *4* – site 4 (luvic chernozem, southern exposure)

Sample procedures. About 1 kg of composite soil sample was selected on each of the 4 sites. Aggregate composition, water-resistant aggregates, soil organic matter and granulometric composition were determined in formally identified layers of the soil 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 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. Aggregate-size distribution, size distribution of water-stable aggregates, particle size distribution and soil organic matter were determined in accordance with the “Soil Sampling and Methods of Analysis” (Carter, Gregorich, 2008). Aggregate size distribution of soils was determined by dry sieving through a standard set of sieves of 10, 7, 5, 3, 2, 1, 0.5 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. Soil organic matter was determined by the oxidimetric method. Soil organic matter was oxidised by a solution of potassium dichromate ($K_2Cr_2O_7$) at a temperature of 140–150 °C, followed by quantitative determination of the portion that was unreacted with Mohr’s salt ($(NH_4)_2SO_4 \bullet FeSO_4 \bullet 6H_2O$). 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.

Statistical analysis. All measurements of the physical properties of soils were carried out in triplicate. 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 (mean ± standard deviation). Differences between values were also assessed using analysis of variance, with statistical significance considered at $P < 0.05$. Data grouping was carried out using cluster analysis (Unweighted pair-group average, Chebychev distance metric). The relationship between values was determined using correlation analysis, with statistical significance considered at $P < 0.05$.

Results

Aggregate-size distribution. As a result of the study of the aggregate composition (Table 1), it was established that the maximum content of aggregates of the > 10 mm fraction was found in the 80–100 cm layer of ordinary (calcic) chernozems and luvic chernozems located on the slopes of northern and southern exposure. The minimum content of aggregates of this fraction was found in the 0–20 cm layer of all studied soils. The maximum content of aggregates of the 7–10 mm fraction was found in the layer 60–80 cm of ordinary chernozem, located on a slope of northern exposure (22.4%), in other soils the maximum content of aggregates of this fraction was found in the 80–100 cm layer. The minimum content of aggregates of the 7–10 mm fraction 10 mm was found in the 20–40 cm layer of luvic chernozem located on a slope of northern exposure (1.8%), in other soils – in the 0–20 cm layer.

Table 1
Aggregate size distribution of chernozems (x ±SD), n = 3

Aggregate size	Depth, cm	North facing slope		South facing slope	
		Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation	Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation
> 10 mm	0–20	2.75 ± 0.53	0.00 ± 0.00	11.05 ± 2.21	1.20 ± 0.46
	20–40	17.21 ± 4.89	0.00 ± 0.00	11.15 ± 2.72	2.40 ± 0.64
	40–60	15.10 ± 2.78	0.00 ± 0.00	13.50 ± 4.12	1.85 ± 0.59
	60–80	13.00 ± 2.68	20.90 ± 4.43	15.60 ± 3.92	1.30 ± 0.31
	80–100	20.01 ± 3.21	41.80 ± 8.09	17.71 ± 4.94	10.90 ± 2.67
7–10 mm	0–20	6.71 ± 1.94	2.15 ± 0.43	12.75 ± 3.58	4.50 ± 0.52
	20–40	15.82 ± 3.95	1.75 ± 0.37	15.12 ± 3.85	7.11 ± 2.01
	40–60	19.11 ± 4.45	2.30 ± 0.53	19.32 ± 5.04	6.55 ± 2.01
	60–80	22.40 ± 5.15	9.07 ± 2.24	23.52 ± 5.92	6.04 ± 2.06
	80–100	15.10 ± 3.23	15.71 ± 3.50	27.10 ± 5.46	10.45 ± 3.07
5–7 mm	0–20	8.31 ± 2.27	5.75 ± 1.27	16.85 ± 3.02	15.25 ± 3.87
	20–40	18.89 ± 4.67	8.23 ± 3.06	18.65 ± 3.91	27.04 ± 5.50
	40–60	18.97 ± 4.26	11.20 ± 2.65	19.80 ± 5.22	26.05 ± 5.54
	60–80	19.11 ± 6.09	12.05 ± 3.83	20.41 ± 5.03	25.10 ± 3.86
	80–100	15.31 ± 3.30	12.90 ± 3.68	21.51 ± 3.87	17.50 ± 3.95
3–5 mm	0–20	16.25 ± 3.36	14.80 ± 3.29	15.65 ± 3.04	17.70 ± 3.89
	20–40	22.53 ± 4.34	20.70 ± 3.19	16.95 ± 4.27	31.20 ± 6.09
	40–60	18.40 ± 4.05	21.80 ± 3.57	18.32 ± 3.44	27.90 ± 4.66
	60–80	14.30 ± 3.76	14.25 ± 3.98	15.21 ± 3.18	24.62 ± 4.49
	80–100	13.80 ± 3.74	6.69 ± 2.46	13.03 ± 2.64	16.20 ± 3.22
2–3 mm	0–20	18.15 ± 4.41	26.50 ± 3.75	12.61 ± 2.60	10.65 ± 2.80
	20–40	9.01 ± 2.57	28.01 ± 3.87	12.25 ± 2.76	10.71 ± 2.83
	40–60	7.85 ± 1.99	26.61 ± 4.26	10.30 ± 2.18	13.50 ± 3.40
	60–80	6.71 ± 2.03	16.75 ± 2.94	7.32 ± 2.33	16.32 ± 3.57
	80–100	7.60 ± 2.08	6.68 ± 1.69	5.60 ± 1.29	13.30 ± 3.23
1–2 mm	0–20	21.95 ± 4.58	26.81 ± 3.93	12.12 ± 2.48	21.75 ± 3.82
	20–40	5.02 ± 1.48	21.20 ± 4.02	9.75 ± 2.60	8.22 ± 2.01
	40–60	5.90 ± 1.33	19.47 ± 2.89	7.31 ± 1.79	11.05 ± 2.82
	60–80	6.81 ± 1.55	12.89 ± 2.10	5.10 ± 1.09	13.90 ± 2.42
	80–100	8.40 ± 1.29	6.31 ± 2.20	3.30 ± 0.56	15.50 ± 2.97
0.5–1 mm	0–20	14.30 ± 2.59	13.50 ± 2.16	9.30 ± 1.26	19.00 ± 4.45
	20–40	5.10 ± 1.12	9.40 ± 2.18	6.00 ± 0.84	6.50 ± 0.48
	40–60	5.50 ± 0.92	8.80 ± 1.43	6.00 ± 0.73	6.40 ± 0.55
	60–80	5.90 ± 1.35	7.00 ± 1.69	4.30 ± 0.59	6.30 ± 0.48
	80–100	7.20 ± 1.09	5.20 ± 1.31	2.00 ± 0.75	10.25 ± 2.33
0.25–0.5 mm	0–20	6.45 ± 1.55	4.35 ± 1.32	5.30 ± 0.71	5.30 ± 1.15
	20–40	2.90 ± 0.66	3.75 ± 1.12	3.05 ± 0.49	3.80 ± 0.56
	40–60	3.70 ± 0.86	2.90 ± 0.66	2.30 ± 0.68	2.60 ± 0.65
	60–80	4.50 ± 1.39	2.85 ± 0.56	1.80 ± 0.52	1.40 ± 0.44
	80–100	5.00 ± 1.35	2.80 ± 0.71	1.10 ± 0.24	2.55 ± 0.52
< 0.25 mm	0–20	5.05 ± 1.16	6.15 ± 1.08	4.40 ± 0.81	4.60 ± 0.63
	20–40	3.70 ± 0.75	6.80 ± 1.11	7.15 ± 0.74	3.00 ± 0.65
	40–60	5.55 ± 1.04	6.90 ± 0.95	3.20 ± 0.52	4.05 ± 0.79
	60–80	7.40 ± 1.23	4.30 ± 0.59	6.80 ± 0.93	5.10 ± 0.97
	80–100	7.80 ± 1.18	1.70 ± 0.34	8.80 ± 1.13	3.40 ± 0.58

The maximum content of aggregates of the 5–7 mm fraction was found in the 60–80 cm layer of ordinary chernozem, located on a slope of northern exposure (19.1%), in the layer 80–100 cm of luvic chernozem, located on a slope of northern exposure (12.9%) and ordinary chernozem, located on a slope of southern exposure (21.5%), as well as in the 20–40 cm layer of luvic chernozem located on a slope of southern exposure (27.0%). The minimum content of aggregates of this fraction was found in the 0–20 cm layer of all soils.

The maximum content of aggregates of the 3–5 mm fraction was found in the 20–40 cm layer of ordinary chernozem located on a slope of northern exposure (22.5%) and luvic chernozem located on a slope of southern exposure (31.2%), as well as in the 40–60 cm layer of luvic chernozem located on a slope of northern exposure (21.8%) and ordinary chernozem located on a slope of southern exposure (18.3%). The minimum content of this fraction of aggregates was found in the 80–100 cm layer of all soils.

The maximum content of aggregates of the 2–3 mm fraction was found in the 0–20 cm layer of ordinary chernozems located on the slopes of northern and southern exposures (18.2% and 12.6%, respectively), in the 20–40 cm layer of luvic chernozems located on the slopes of northern exposure (28.0 %), and in the layer 60–80 cm of luvic chernozem located on a slope of southern exposure (16.3%). The minimum content of this fraction of aggregates was found in the 60–80 cm layer of ordinary chernozem located on a slope of northern exposure (6.7%), in the 80–100 cm layer of luvic chernozem located on a slope of northern exposure (6.7%), and ordinary chernozem located on a slope southern exposure (5.6%), as well as in the 0–10 cm layer of luvic chernozem located on a slope of southern exposure (10.7%).

The maximum content of aggregates of the 1–2 mm fraction was found in the 0–20 cm layer of all soils, and the minimum content of this fraction of aggregates was found in the 20–40 cm layer of ordinary chernozem located on a slope of northern exposure (5.0%) and luvic chernozem located on a slope southern exposure (8.2%), as well as in the 80–100 cm layer of luvic chernozem located on a slope of northern exposure (6.3%), and ordinary chernozem located on a slope of southern exposure (3.3%).

The maximum content of aggregates of the 0.5–1.0 mm fraction was found in the 0–20 cm layer of all soils. The minimum content of this fraction of aggregates was found in the 20–40 cm layer of ordinary chernozem located on a slope of northern exposure, in the 80–100 cm layer of luvic chernozem located on a slope of northern exposure (5.2%), and ordinary chernozem located on a slope of southern exposure (2.0 %), as well as in the 60–80 cm layer of luvic chernozem located on a slope of southern exposure (6.3%).

The maximum content of aggregates of the 0.25–0.50 mm fraction was found in the 0–20 cm layer of all soils. The minimum content of this fraction of aggregates was found in the 20–40 cm layer of ordinary chernozem located on a slope of northern exposure (2.9%), in the 80–100 cm layer of luvic chernozem located on a slope of northern exposure (2.8%), and ordinary chernozem located on a slope southern exposure (1.1%), as well as in the 80–100 cm layer of luvic chernozem located on a slope with southern exposure.

The maximum content of fraction aggregates <0.25 mm was found in the 80–100 cm layer of ordinary chernozems located on the slopes of northern and southern exposures (7.8% and 8.8%, respectively), as well as in the 40–60 cm layer of luvic chernozems located on the slopes of northern exposure (6.9%), and in a layer of 60–80 cm of luvic chernozem located on a slope of southern exposure (5.1%). The minimum content of this fraction of aggregates was found in the 20–40 cm layer of ordinary chernozem located on a slope of northern exposure (3.7%) and luvic chernozem located on a slope of southern exposure (3.0%), in the 80–100 cm layer of luvic chernozem located on a slope northern exposure (1.7%), as well as in the 40–60 cm layer of ordinary chernozem located on a slope with southern exposure (3.2%).

Table 2
Assessment of the influence of forest ecosystems
on the aggregate composition of soils (n = 15)

Fraction aggregate size, mm	North facing slope		South facing slope	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
> 10	0.07*	0.8*	75.64	$5.1 \cdot 10^{-7}$
7–10	26.46	$1.5 \cdot 10^{-4}$	83.30	$2.9 \cdot 10^{-7}$
5–7	16.99	$1.0 \cdot 10^{-3}$	1.84*	0.20*
3–5	0.87*	0.37*	15.43	$1.5 \cdot 10^{-3}$
2–3	26.07	$1.6 \cdot 10^{-4}$	5.10	0.04
1–2	16.97	$1.0 \cdot 10^{-3}$	20.84	$4.4 \cdot 10^{-4}$
0.5–1	2.14*	0.17*	13.80	$2.3 \cdot 10^{-3}$
0.25–0.5	13.34	$2.6 \cdot 10^{-3}$	6.56	0.03
< 0.25	0.63*	0.44*	9.87	$7.2 \cdot 10^{-3}$

Note: *A significant effect was not established at $P < 0.05$.

Two-factor analysis of variance confirmed a significant difference between ordinary chernozems and luvic chernozems, located on a slope of northern exposure, in the content of aggregates of fractions 7–10, 5–7, 2–3, 1–2, 0.25–0.50 mm. Under conditions of southern exposure, a significant difference between these soils was confirmed in the content of aggregates of all fractions, except for the 5–7 mm fraction (Table 2).

A significant difference was also confirmed between ordinary chernozems on the slopes of northern and southern exposures in the content of aggregates of fractions 0.5–1.0 and 0.25–0.50 mm, as well as between luvic chernozems of northern and southern exposures in the content of aggregates of fractions > 10, 5–7, 3–5 and 2 –3 mm (Table 3).

Table 3
Assessment of the influence of slope exposure
on the aggregate composition of soils (n = 15)

Size of fraction aggregates, mm	Steppe vegetation		Forest vegetation	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
> 10	0.01*	0.9*	5.49	0.03
7–10	3.19*	0.1*	0.28*	0.61*
5–7	4.60*	0.05*	58.95	$2.2 \cdot 10^{-6}$
3–5	1.94*	0.19*	30.41	$7.6 \cdot 10^{-5}$
2–3	0.05*	0.83*	8.72	0.01
1–2	2.05*	0.17*	2.30*	0.15*
0.5–1	6.83	0.02	0.71*	0.42*
0.25–0.5	19.82	$5.5 \cdot 10^{-4}$	0.87*	0.37*
<0.25	0.10*	0.75*	3.96*	0.07*

Note: *no significant effect was established at $P < 0.05$.

As a result of cluster analysis, it was found that the data, depending on the size of the aggregates, can be conditionally divided into three groups (Fig. 2): in the first group (SS(>10), FS(7–10), SS(7–10), FS (2–3), SN(5–7), FS(>10), FN(>10), SN(<0.25), FN(7–10), SS (<0.25), SN(>10), SN(7–10), FN(5–7), SS(5–7)) aggregates of fractions 5–> 10 mm predominate, in the second group (FS(5–7), FS(3–5), FN(3–5), FN(2–3), FN(<0.25), SS(3–5), SN(3–5)) aggregates of fractions 3–5 mm predominate, in the third group (SS(2–3), SS(1–2), FN(1–2), SS(0.5–1), SS(0.25–0.5), FN(0.5–1), FS(0.25–0.5), FN(0.25–0.5), SN(2–3), SN(1–2), SN(0.5–1), FS(0.5–1), FS(1–2), SN(0.25–0.5), FS(<0.25)) aggregates predominate fractions 0.25–2.00 mm.

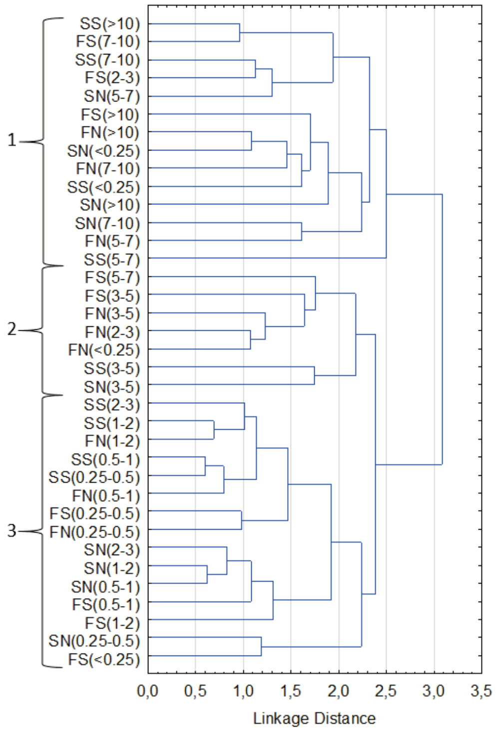

Fig. 2. Results of cluster analysis (unweighted pair-group average, Chebychev distance metric) of data on the content of aggregates of fractions >10, 7–10, 5–7, 3–5, 2–3, 1–2, 0.5–1.0, 0.25–0.50 and < 0.25 mm in ordinary chernozems under steppe vegetation (S) and in luvic chernozems under forest vegetation (F) under conditions of slopes of northern (N) and southern (S) exposure

Size distribution of water-stable aggregates. Studies of water-stable chernozem aggregates (Table 4) revealed that the maximum content of their fraction >5 mm was found in the 80–100 cm layer of ordinary chernozem located on a slope of northern exposure (11.3%), as well as in the layer 0–20 cm of other soils. The minimum content of water-stable aggregates of the >5 mm fraction was found in the 0–20 cm layer ordinary chernozem located on a slope of northern exposure (3.9%) and in the 80–100 cm layer of other soils.

The maximum content of water-stable aggregates of the 3–5 mm fraction was found in the 0–20 cm layer of all soils, and the minimum – in the 80–100 cm layer of ordinary chernozems located on the slopes of northern and southern exposures (0.9% and 1.8%, respectively), luvic chernozem located on a slope with a northern exposure (2.3%), as well as in the 60–80 cm layer of luvic chernozem located on a southern exposure (1.9%). The maximum content of water-stable aggregates of fractions 2–3 and 1–2 mm was found in the 0–20 cm layer of all soils. The minimum content of water-stable aggregates of these fractions was found in the 80–100 cm layer of all soils.

The maximum content of water-stable aggregates of the 0.5–1 mm fraction was found in the 60–80 cm layer of ordinary chernozem, located on a slope of northern exposure (20.1%), in the 40–60 cm layer of luvic chernozem, located on a slope of northern exposure (27.8%), as well as in the 0–20 cm layer of ordinary chernozem and luvic chernozem, located on a slope of southern exposure (13.9% and 15.5%, respectively). The minimum content of water-stable aggregates of this fraction was revealed in the layer of 0–20 cm of ordinary chernozem and luvic chernozem located on a slope of northern exposure (16.9% and 18.1%, respectively) and in the 80–100 cm layer of ordinary chernozem and luvic chernozem located on a slope of southern exposure (7.3% and 12.6% respectively).

Table 4
Size distribution of water-stable aggregates of chernozems (x ± SD, n = 3)

Size of water-stable aggregates	Depth, cm	North facing slope		South facing slope	
		Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation	Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation
> 5 mm	0–20	3.85 ± 0.26	10.25 ± 2.25	4.85 ± 0.85	8.55 ± 0.75
	20–40	6.27 ± 0.55	4.20 ± 1.10	3.95 ± 0.75	5.30 ± 0.60
	40–60	7.60 ± 0.40	3.17 ± 1.05	3.50 ± 0.70	4.55 ± 0.55
	60–80	8.87 ± 0.85	2.00 ± 0.50	3.00 ± 0.50	3.83 ± 0.75
	80–100	11.30 ± 1.30	0.80 ± 0.20	2.07 ± 0.65	3.45 ± 0.65
3–5 mm	0–20	13.30 ± 1.50	11.15 ± 1.46	9.55 ± 0.65	7.40 ± 0.49
	20–40	7.09 ± 1.02	3.95 ± 0.38	3.15 ± 0.51	2.49 ± 0.38
	40–60	4.85 ± 0.65	2.80 ± 0.32	2.80 ± 0.47	2.20 ± 0.32
	60–80	2.60 ± 0.62	2.55 ± 0.23	2.10 ± 0.26	1.91 ± 0.17
	80–100	0.90 ± 0.13	2.30 ± 0.28	1.80 ± 0.18	2.25 ± 0.26
2–3 mm	0–20	12.75 ± 2.13	9.75 ± 1.14	9.90 ± 2.04	5.55 ± 0.66
	20–40	10.08 ± 0.85	6.02 ± 0.72	5.10 ± 0.84	2.70 ± 0.19
	40–60	8.15 ± 0.73	4.80 ± 0.47	4.30 ± 0.48	2.40 ± 0.38
	60–80	6.20 ± 0.57	3.85 ± 0.67	2.80 ± 0.37	2.12 ± 0.22
	80–100	1.70 ± 0.27	2.90 ± 0.55	1.50 ± 0.26	1.80 ± 0.28
1–2 mm	0–20	21.05 ± 4.34	9.55 ± 3.00	13.30 ± 3.14	9.35 ± 2.54
	20–40	14.30 ± 3.92	7.30 ± 1.32	8.90 ± 1.68	6.80 ± 1.09
	40–60	14.25 ± 2.97	6.30 ± 1.57	7.50 ± 1.95	5.60 ± 0.72
	60–80	14.20 ± 2.68	5.10 ± 0.56	5.20 ± 0.75	4.40 ± 0.51
	80–100	4.30 ± 0.51	3.90 ± 0.39	3.80 ± 0.58	3.75 ± 0.54
0.5–1.0 mm	0–20	16.85 ± 3.71	18.10 ± 4.02	13.90 ± 4.49	15.45 ± 4.66
	20–40	18.33 ± 3.99	27.55 ± 6.30	11.25 ± 3.97	15.20 ± 5.09
	40–60	19.20 ± 4.35	27.80 ± 6.22	10.20 ± 2.69	14.65 ± 3.79
	60–80	20.10 ± 4.45	23.35 ± 5.20	8.30 ± 2.19	14.10 ± 5.08
	80–100	9.70 ± 1.85	18.90 ± 4.57	7.30 ± 1.47	12.60 ± 3.96
0.25–0.50 mm	0–20	11.15 ± 2.63	14.90 ± 3.69	11.20 ± 3.15	17.49 ± 4.94
	20–40	18.80 ± 4.58	21.21 ± 4.11	19.35 ± 4.99	22.29 ± 5.04
	40–60	20.05 ± 5.84	22.30 ± 5.42	23.50 ± 4.72	21.35 ± 4.84
	60–80	21.30 ± 5.08	25.60 ± 4.29	20.40 ± 4.07	20.40 ± 4.98
	80–100	28.60 ± 4.38	28.90 ± 4.79	18.30 ± 2.99	19.85 ± 4.70
< 0.25 mm	0–20	21.05 ± 5.16	26.30 ± 4.93	37.36 ± 7.17	36.21 ± 4.01
	20–40	25.11 ± 6.01	29.79 ± 4.03	48.31 ± 7.28	45.20 ± 7.13
	40–60	25.91 ± 6.24	32.80 ± 5.69	48.22 ± 7.99	49.25 ± 7.03
	60–80	26.71 ± 6.51	37.55 ± 7.27	58.22 ± 10.11	53.31 ± 6.91
	80–100	43.50 ± 7.79	42.30 ± 5.92	65.21 ± 7.41	56.32 ± 8.67

The maximum content of water-stable aggregates of the 0.25–0.50 mm fraction was revealed in the 80–100 cm layer of ordinary chernozem and luvic chernozem located on a slope of northern exposure (28.6% and 28.9%, respectively), as well as in the 40–60 cm layer of ordinary chernozem (23.5%) and in the 20–40 cm layer of luvic chernozem (22.3%), located on a slope of southern exposure. The minimum content of water-stable aggregates of this fraction was found in the 0–20 cm layer of all soils.

The maximum content of water-stable aggregates of the <0.25 mm fraction was found in the 80–100 cm layer of all soils, and the minimum content was found in the 0–20 cm layer of all soils.

Two-factor analysis of variance confirmed a significant difference between ordinary chernozems and luvic chernozems, located on a slope of northern exposure, in the content of water-stable aggregates of all fractions. Under conditions of southern exposure, a significant difference between these soils was confirmed in the content of water-stable aggregates of all fractions, except for fractions 0.25–0.50 and <0.25 mm (Table 5). A significant difference was also confirmed between ordinary chernozems of northern and southern exposures in the content of water-stable aggregates of all fractions, except for the 0.25–0.5 mm fraction, as well as between luvic chernozems of northern and southern exposures in the content of water-stable aggregates of fractions > 5, 3–5, 2–3, 0.5–1.0 and <0.25 mm (Table 6).

Table 5
Assessment of the influence of forest ecosystems
on the content of water-stable soil aggregates (n = 15)

Fraction size of waterproof aggregates, mm	North facing slope		South facing slope	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
>5	5.15	0.04	21.06	$4.2 \cdot 10^{-4}$
3–5	7.19	0.02	6.54	0.02
2–3	14.88	$1.7 \cdot 10^{-3}$	11.99	$3.8 \cdot 10^{-3}$
1–2	39.04	$2.1 \cdot 10^{-5}$	14.58	$1.9 \cdot 10^{-3}$
0.5–1.0	40.70	$1.7 \cdot 10^{-5}$	25.10	$1.9 \cdot 10^{-4}$
0.25–0.50	42.29	$1.4 \cdot 10^{-5}$	0.85*	0.37*
<0.25	7.29	0.02	1.89*	0.19*

Note: *no significant effect was established at P < 0.05.

As a result of cluster analysis, it was established that the data, depending on the size of water-stable aggregates, can be conditionally divided into two groups (Fig. 3): in the first group (SS(>5), FS(1–2), SS(0.5–1), SS(2–3), FN(2–3), SS(1–2), SS(3–5), FN(3–5), FS(2–3), FS (3–5), FS

(>5), FN(>5), SN(3–5), SN(1–2), FN(1–2), SN(2–3)) water-stable aggregates of fractions 1–>5 mm predominate, in the second group (SS(0.25–0.5), FN(0.5–1), SN(0.5–1), FS(0.5–1), FS(0.25–0.5), SS(<0.25), SN(<0.25), FS(<0.25), FN(<0.25), SN(>5), FN(0.25–0.5), SN(0.25–0.5)) water-stable aggregates of fractions <0.25–1.00 mm predominate.

Table 6
Assessment of the influence of slope exposure
on the content of water-stable soil aggregates (n = 15)

Fraction size of waterproof aggregates, mm	Steppe vegetation		Forest vegetation	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
>5	19.44	$5.9 \cdot 10^{-4}$	5.47	0.04
3–5	13.44	$2.5 \cdot 10^{-3}$	12.45	$3.3 \cdot 10^{-3}$
2–3	25.95	$1.6 \cdot 10^{-4}$	48.42	$6.7 \cdot 10^{-6}$
1–2	21.88	$3.6 \cdot 10^{-4}$	0.57*	0.47*
0.5–1.0	20.26	$5.0 \cdot 10^{-4}$	29.81	$8.4 \cdot 10^{-5}$
0.25–0.50	0.71*	0.41*	1.89*	0.19*
<0.25	101.41	$8.6 \cdot 10^{-8}$	34.94	$3.8 \cdot 10^{-5}$

Note: *significant effect not established at $P < 0.05$.

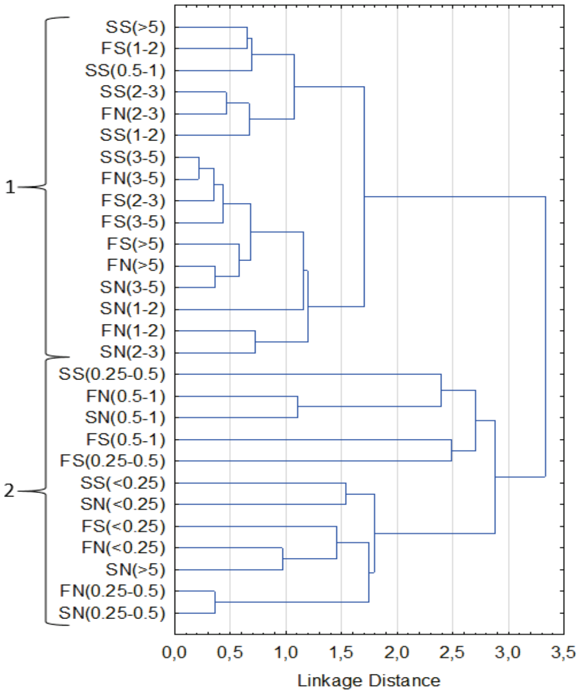

Fig. 3. Results of cluster analysis (unweighted pair-group average, Chebychev distance metric) of data on the content of water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2, 0.5–1.0, 0.25–0.50 and <0.25 mm in ordinary chernozems under steppe vegetation (S) and in luvic chernozems under forest vegetation (F) in conditions of slopes of northern (N) and southern (S) exposure

Soil organic matter content. As a result of the study, it was established that under conditions of a northern slope, the maximum content of soil organic matter was found in ordinary chernozem and luvic chernozem (Table 7) in the 0–20 cm layer (5.7% and 6.9%, respectively), the minimum content was in the 80–100 cm layer of ordinary chernozem (0.1%) and luvic chernozem (1.0%). Under the conditions of a slope of southern exposure, the maximum content of organic matter in ordinary chernozem and luvic chernozem was found in the 0–20 cm layer (5.4% and 6.9%, respectively), the minimum content was in the 80–100 cm layer of ordinary chernozem (0.1%) and luvic chernozem (2.5%).

Ordinary chernozems are characterized by a lower average content of soil organic matter in the 0–100 cm layer compared to luvic chernozems under conditions of northern (by 1.1%) and southern (by 2.0%) exposures.

Ordinary chernozems of northern and southern exposures practically do not differ from each other in the average content of soil organic matter in the 0–100 cm layer (2.12% and 2.14%, respectively). Luvic chernozem of northern exposure is characterized by a lower content of organic matter in the 0–100 cm layer compared to luvic chernozem of southern exposure (3.2% and 4.1%, respectively).

Analysis of variance confirmed a significant difference in the content of soil organic matter between luvic chernozems of northern and southern exposure ($F = 49.03$, $P = 6.23\ 10^{-6}$), as well as between ordinary chernozems and luvic chernozems ($F = 186.17$, $P = 3.8\ 10^{-6}$).

Table 7
Content of soil organic matter (%) of chernozems (x ± SD, n = 3)

Depth, cm	North facing slope		South facing slope	
	Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation	Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation
0–20	5.74 ± 0.15	6.88 ± 0.20	5.38 ± 0.11	6.94 ± 0.17
20–40	2.13 ± 0.12	3.94 ± 0.10	2.73 ± 0.14	4.79 ± 0.13
40–60	1.40 ± 0.10	2.37 ± 0.13	1.46 ± 0.09	3.69 ± 0.19
60–80	1.22 ± 0.11	1.70 ± 0.10	1.00 ± 0.10	2.67 ± 0.12
80–100	0.10 ± 0.02	1.02 ± 0.04	0.12 ± 0.03	2.53 ± 0.10

Particle size distribution. As a result of the study of the particle size distribution, it was established that ordinary chernozems under steppe vegetation and luvic chernozems under forest vegetation belong to the silty clay loam granulometric class (Table 8).

Under the conditions of a slope of northern exposure, the maximum sand content in ordinary chernozem and luvic chernozem was found in the 0–20 cm layer (15.2% and 19.8%, respectively), the minimum in ordinary chernozem in the 60–80 cm layer (7.4%) and in luvic chernozem in the 80–100 cm layer (13.1%). The maximum silt content in ordinary chernozem was found in the 80–100 cm layer (54.1%) and in luvic chernozem in the 0–20 cm layer (62.5%), the minimum – in ordinary chernozem in the 20–40 cm layer (52.6%) and in luvic chernozem in the 40–60 cm layer (51.6%). The maximum clay content in ordinary chernozem was found in the 60–80 cm layer (39.4%) and in luvic chernozem in the 80–100 cm layer (32.9%), the minimum in ordinary chernozem and luvic chernozem in the 0–20 cm layer (31.6% and 17.7% respectively).

Table 8
Particle size distribution of chernozems (x ± SD, n = 3)

Depth, cm		North facing slope		South facing slope	
		Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation	Calcic Chernozem under steppe vegetation	Luvic Chernozem under natural forest vegetation
Sand, %	0–20	15.23 ± 2.27	19.80 ± 1.50	23.67 ± 1.40	18.17 ± 1.01
	20–40	15.10 ± 1.25	16.60 ± 0.90	13.40 ± 1.41	13.47 ± 1.33
	40–60	11.47 ± 1.20	16.37 ± 2.85	10.17 ± 1.00	11.67 ± 1.27
	60–80	7.40 ± 1.01	14.17 ± 1.06	7.40 ± 0.56	9.70 ± 0.56
	80–100	10.30 ± 1.15	13.10 ± 2.43	5.47 ± 0.57	10.33 ± 0.61
Silt, %	0–20	53.13 ± 1.11	62.53 ± 4.18	52.73 ± 1.46	48.90 ± 4.28
	20–40	52.63 ± 0.57	58.87 ± 3.37	55.17 ± 0.95	49.70 ± 2.51
	40–60	53.17 ± 1.00	51.63 ± 1.15	57.60 ± 1.40	45.87 ± 2.56
	60–80	53.23 ± 1.16	53.90 ± 1.44	58.23 ± 0.86	41.67 ± 2.08
	80–100	54.10 ± 1.97	54.00 ± 1.66	59.23 ± 0.90	40.03 ± 1.79
Clay, %	0–20	31.63 ± 1.46	17.67 ± 1.42	23.60 ± 1.55	32.97 ± 2.32
	20–40	32.27 ± 1.46	24.54 ± 1.43	31.43 ± 1.31	36.83 ± 2.02
	40–60	35.37 ± 1.01	32.01 ± 1.59	32.23 ± 0.50	42.50 ± 1.54
	60–80	39.37 ± 1.21	31.93 ± 1.96	34.37 ± 1.12	48.67 ± 2.14
	80–100	35.60 ± 0.96	32.91 ± 2.59	35.30 ± 0.72	49.63 ± 2.19

Under conditions of a southern exposure slope, the maximum sand content in ordinary chernozem and luvic chernozem was found in the 0–20 cm layer (23.7% and 18.2%, respectively), the minimum in ordinary chernozem in the 80–100 cm layer (5.5%) and in luvic chernozem in the 60–80 cm layer (9.7%). The maximum silt content in ordinary chernozem was found in the 80–100 cm layer (59.2%) and in luvic chernozem in the 20–40 cm layer (49.7%). The maximum clay content was found in ordinary chernozem and luvic chernozem in the 80–100 cm layer (35.3% and 49.6%, respectively), the minimum in ordinary chernozem and luvic chernozem in the 0–20 cm layer (23.6% and 33.0%, respectively).

Under the conditions of a slope of northern exposure, according to the average content in the 0–100 cm layer, luvic chernozem is characterized by an increased content of sand and silt (16.0% and 56.2%, respectively) and a lower content of clay (27.8%) compared to ordinary chernozem (11.9%, 53.3% and 34.9% respectively).

Under the conditions of a slope of southern exposure, according to the average content in the 0–100 cm layer, luvic chernozem is characterized by an increased content of clay (42.1%) and a lower content of silt (45.2%) compared to ordinary chernozem (31.4% and 56.6%, respectively) and practically does not differ in sand content (12.7% and 12.0% respectively).

In terms of average content in the 0–100 cm layer, ordinary chernozem under conditions of a slope of northern exposure is distinguished by an increased content of clay (by 3.5%) and a reduced content of silt (by 3.3%) compared to ordinary chernozem under conditions of a slope of southern exposure and practically does not differ in content of sand. Luvic chernozem under conditions of a slope of northern exposure, based on the average content in the 0–100 cm layer, is distinguished by an increased content of sand (by 3.3%) and silt (by 11.0%) and a reduced content of clay (by 14.3%) compared to luvic chernozem on a slope of southern exposure.

As a result of cluster analysis, it was established that the data can be conditionally divided into two groups (Fig. 4): the first group includes the sand content in ordinary chernozems and luvic chernozems on the slopes of the northern (SaSN and SaFN) and southern (SaSS and SaFS) exposures, as well as silt content in luvic chernozems on slopes of northern and southern exposures (SiFN and SiFS); The second group includes the clay content in ordinary chernozems and luvic chernozems on the slopes of the northern (ClSN and ClFN) and southern (ClSS and ClFS) exposures, as well as the silt content in ordinary chernozems on the northern and southern slopes (SiSN and SiSS).

Two-factor analysis of variance (Tables 9 and 10) confirmed a significant difference between ordinary chernozems on the northern and southern slopes in terms of silt and clay content, between luvic chernozems on northern and southern slopes in terms of sand, silt and clay content, between ordinary chernozems and luvic chernozems in terms of the content of sand, silt and clay.

The relationship between the content of soil organic matter and particle size distribution with the aggregate composition and content of water-stable aggregates. In order to study the relationships between the content of soil organic matter, sand, silt and clay and the aggregate composition and content of water-stable aggregates, we performed a correlation analysis.

As a result of a study of ordinary chernozem located on a slope of northern exposure (Table 11), it was established that there is a close direct relationship between the content of soil organic matter ($r \geq 0.70$) with the content of aggregates of fractions 2–3, 1–2, 0.5–1.0 mm, water-stable aggregates of fractions 3–5, 2–3, 1–2 mm and close feedback ($r \geq -0.70$) with the content of aggregates of fraction > 10 mm and water-stable aggregates of fractions > 5, 0.25–0.50 mm. There is a close direct relationship between the sand content and the content of water-stable aggregates of the 3–5 and 2–3 mm fractions.

Studies of luvic chernozem located on a slope of northern exposure (Table 12) have established that there is a close direct relationship between the content of soil organic matter and the content of aggregates of fractions 1–2, 0.5–1 mm, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm and close feedback with the content of aggregates of the 5–7 mm fraction and water-stable aggregates of the 0.25–0.50 mm fraction. There is a close direct relationship between the sand content with the content of aggregates of fractions 2–3, 1–2, 0.5–1.0 mm, water-stable aggregates of fractions > 5, 3–5, 2–3 mm, and a close inverse relationship with the content of aggregates of the fraction > 10 mm and content of water-stable aggregates fraction < 0.25 mm. There is a close direct relationship between the silt content and the content of water-stable aggregates of the fraction > 5, 3–5, 1–2 mm. There is a close direct relationship between the clay content and the content of aggregates of the 5–7 mm fraction, water-stable aggregates of the 0.25–0.50 mm fraction, and a close inverse relationship between the content of aggregates of the 1–2, 0.5–1.0 mm fractions, water-stable aggregates of the fractions > 5, 3– 5, 2–3, 1–2 mm.

As a result of a study of ordinary chernozem located on a slope of southern exposure (Table 13), it was established that there is a close direct relationship between the content of soil organic matter and the content of aggregates of fractions 2–3, 1–2, 0.5–1.0, 0.25–0.50 mm, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm and close feedback with the content of aggregates of the 7–10 mm fraction and water-stable aggregates of the < 0.25 mm fraction. There is a close direct relationship between the sand content and the content of aggregates of fractions 2–3, 1–2, 0.5–1.0, 0.25–0.50, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm and close feedback with the content of aggregates of the 7–10 mm fraction and water-stable aggregates of the <0.25 mm fraction. There is a close direct relationship between the silt content with the content of aggregates of the 7–10 mm fraction and a close inverse relationship with the content of aggregates of the fractions 1–2, 0.5–1.0, 0.25–0.50 mm, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2, 0.5–1.0 mm. There is a close direct relationship between the clay content and the content of aggregates of the 7–10 mm fraction and a close inverse relationship between the content of aggregates of fractions 1–2, 0.5–1.0, 0.25–0.50 mm, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2, 0.5–1 mm.

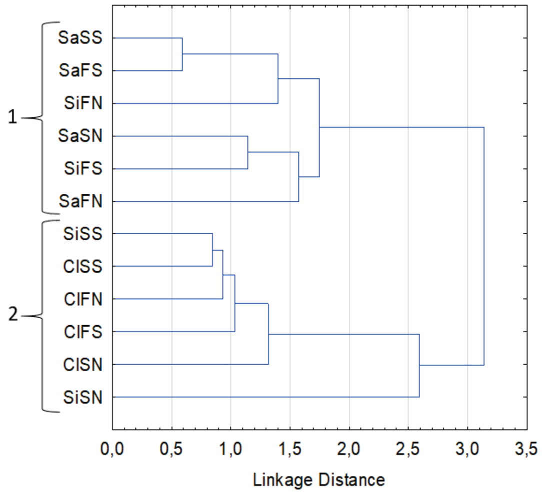

Fig. 4. Results of cluster analysis (Unweighted pair-group average, Chebychev distance metric) of data on the content of sand (Sa), silt (Si) and clay (Cl) in ordinary chernozems under steppe vegetation (S) and in luvic chernozems under natural forest vegetation (F) in conditions of slopes of northern (N) and southern (S) exposure

Table 9
Assessment of the influence of forest ecosystems
on the granulometric composition of soils (n = 15)

Granulometric composition	North facing slope		South facing slope	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
Sand	40.45	$1.8 \cdot 10^{-5}$	0.42*	0.53*
Silt	5.47	0.04	45.38	$9.5 \cdot 10^{-6}$
Clay	33.89	$4.4 \cdot 10^{-5}$	112.46	$4.5 \cdot 10^{-8}$

Note: *no significant effect was established at $P < 0.05$.

Table 10
Assessment of the influence of slope exposure
on the granulometric composition of soils (n = 15)

Granulometric composition	Steppe vegetation		Forest vegetation	
	F ($F_{0.05}$ = 4.60)	P	F ($F_{0.05}$ = 4.60)	P
Sand	0.01*	0.92*	35.98	$3.3 \cdot 10^{-5}$
Silt	26.64	$1.5 \cdot 10^{-4}$	98.61	$1.0 \cdot 10^{-7}$
Clay	16.62	$1.1 \cdot 10^{-3}$	284.78	$1.1 \cdot 10^{-10}$

Note: *significant effect not established at $P < 0.05$.

Studies of luvic chernozem located on a slope of southern exposure (Table 14) have established that there is a close direct relationship between the content of soil organic matter with the content of aggregates of fractions 0.5–1.0, 0.25–0.50 mm, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm and close feedback with the content of water-stable aggregates of the <0.25 mm fraction. There is a close direct relationship between the sand content and the content of aggregates of the 0.25–0.50 fraction, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm, and a close inverse relationship with the content of water-stable aggregates of the fraction < 0.25 mm. There is a close direct relationship between the silt content and the content of aggregates of the 0.25–0.50 mm fraction and water-stable aggregates of the > 5 mm fraction. There is a close relationship between the clay content and the content of aggregates of the 0.25–0.50 fraction, water-stable aggregates of fractions > 5, 3–5, 2–3, 1–2 mm.

Table 11
Empirical correlation coefficients between the content of soil organic matter, the content of sand, silt, clay, the content of aggregates and the content of water-stable aggregates in ordinary chernozem on slopes of northern exposure (n = 15)

Content	SOM	Sa	Si	Cl	D(>10)	D(7-10)	D(5-7)	D(3-5)	D(2-3)	D(1-2)	D(<1)	D(<0.5)	D(<.25)	W(>5)	W(3-5)	W(2-3)	W(1-2)	W(<1)	W(<0.5)
Sa	0.64*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Si	–0.17	–0.14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cl	–0.62*	–0.75*	0.16	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(>10)	–0.84*	–0.33	0.07	0.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(7–10)	–0.68*	–0.64*	–0.01	0.61*	0.46	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(5–7)	–0.60*	–0.32	0.13	0.42	0.39	0.45	–	–	–	–	–	–	–	–	–	–	–	–	–
D(3–5)	0.14	0.61*	–0.01	–0.25	0.12	0.04	–0.06	–	–	–	–	–	–	–	–	–	–	–	–
D(2–3)	0.85*	0.60*	–0.03	–0.58*	–0.72*	–0.66*	–0.43	–0.10	–	–	–	–	–	–	–	–	–	–	–
D(1–2)	0.83*	0.43	0.14	–0.45	–0.74*	–0.64*	–0.68*	–0.17	0.91*	–	–	–	–	–	–	–	–	–	–
D(0.5–1)	0.80*	0.47	–0.01	–0.41	–0.77*	–0.64*	–0.63*	–0.21	0.92*	0.96*	–	–	–	–	–	–	–	–	–
D(0.25–0.5)	0.47	0.13	0.63*	–0.04	–0.42	–0.44	–0.53*	–0.09	0.51	0.76*	0.63*	–	–	–	–	–	–	–	–
D(<0.25)	–0.45	–0.63*	0.69*	0.67*	0.29	0.25	0.05	–0.36	–0.32	–0.03	–0.12	0.54*	–	–	–	–	–	–	–
W(>5)	–0.89*	–0.67*	0.48	0.65*	0.73*	0.48	0.36	–0.23	–0.73*	–0.57*	–0.58*	–0.03	0.77*	–	–	–	–	–	–
W(3–5)	0.97*	0.77*	–0.17	–0.69*	–0.72*	–0.66*	–0.55*	0.31	0.83*	0.76*	0.72*	0.40	–0.53*	–0.91*	–	–	–	–	–
W(2–3)	0.86*	0.70*	–0.25	–0.56*	–0.62*	–0.42	–0.30	0.46	0.68*	0.54*	0.49	0.20	–0.61*	–0.92*	0.93*	–	–	–	–
W(1–2)	0.78*	0.44	–0.12	–0.33	–0.78*	–0.32	–0.04	0.09	0.74*	0.58*	0.55*	0.23	–0.44	–0.83*	0.78*	0.86*	–	–	–
W(0.5–1)	0.24	0.02	–0.08	0.10	–0.03	0.23	0.07	0.37	0.05	0.01	–0.15	0.07	–0.06	–0.32	0.33	0.58*	0.50	–	–
W(0.2–0.5)	–0.79*	–0.45	–0.02	0.47	0.56*	0.52*	0.41	–0.31	–0.47	–0.51	–0.35	–0.43	0.28	0.68*	–0.81*	–0.80*	–0.65*	–0.56*	–
W(<0.25)	–0.58*	–0.35	0.32	0.23	0.74*	0.17	–0.05	–0.24	–0.30	–0.17	–0.23	0.15	0.62*	0.73*	–0.54*	–0.65*	–0.73*	–0.21	0.52*

Note: SOM – soil organic matter; Sa – sand content; Si – silt content; Cl – clay content; D – content of fraction aggregates (mm); W – content of water-resistant fraction aggregates (mm); *the noted correlations were significant at the level P < 0.05.

Table 12
Empirical correlation coefficients between the content of soil organic matter, the content of sand, silt, clay, the content of aggregates and the content of water-stable aggregates in luvic chernozem on slopes of northern exposure (n = 15)

Content	SOM	Sa	Si	Cl	D(>10)	D(>7)	D(5-7)	D(3-5)	D(2-3)	D(1-2)	D(<1)	D(<0.5)	D(<0.25)	W(>5)	W(3-5)	W(2-3)	W(1-2)	W(<1)	W(<0.5)
Sa	0.80*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Si	0.80*	0.61*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cl	–0.95*	–0.62*	–0.82*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(>10)	–0.68*	–0.71*	–0.36	0.56*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(7–10)	–0.67*	–0.57*	–0.36	0.61*	0.92*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(5–7)	–0.71*	–0.55*	–0.53*	0.76*	0.50	0.65*	–	–	–	–	–	–	–	–	–	–	–	–	–
D(3–5)	0.28	0.36	0.10	–0.15	–0.78*	–0.71*	0.04	–	–	–	–	–	–	–	–	–	–	–	–
D(2–3)	0.65*	0.70*	0.45	–0.53*	–0.90*	–0.90*	–0.46	0.81*	–	–	–	–	–	–	–	–	–	–	–
D(1–2)	0.86*	0.90*	0.62*	–0.73*	–0.87*	–0.79*	–0.62*	0.58*	0.85*	–	–	–	–	–	–	–	–	–	–
D(0.5–1)	0.88*	0.81*	0.66*	–0.76*	–0.71*	–0.61*	–0.49	0.46	0.64*	0.91*	–	–	–	–	–	–	–	–	–
D(0.25–0.5)	0.65*	0.48	0.65*	–0.62*	–0.32*	–0.40	–0.48	0.22	0.38	0.63*	0.78*	–	–	–	–	–	–	–	–
D(<0.25)	0.57*	0.61*	0.29	–0.45	–0.91*	–0.86*	–0.37	0.86*	0.86*	0.85*	0.75*	0.53*	–	–	–	–	–	–	–
W(>5)	0.96*	0.79*	0.78*	–0.87*	–0.62*	–0.59*	–0.61*	0.28	0.58*	0.85*	0.95*	0.77*	0.59*	–	–	–	–	–	–
W(3–5)	0.94*	0.74*	0.80*	–0.89*	–0.46	–0.46	–0.63*	0.07	0.45	0.74*	0.85*	0.68*	0.38	0.97*	–	–	–	–	–
W(2–3)	0.96*	0.75*	0.66*	–0.92*	–0.70*	–0.66*	–0.73*	0.22	0.56*	0.81*	0.83*	0.52*	0.55*	0.90*	0.89*	–	–	–	–
W(1–2)	0.83*	0.68*	0.70*	–0.75*	–0.66*	–0.67*	–0.58*	0.43	0.62*	0.83*	0.90*	0.86*	0.73*	0.91*	0.80*	0.74*	–	–	–
W(0.5–1)	–0.14	0.02	–0.23	0.22	–0.36	–0.22	0.31	0.69*	0.27	0.24	0.26	0.26	0.63*	–0.04	–0.28	–0.14	0.21	–	–
W(0.25–0.5)	–0.77*	–0.46	–0.42	0.74*	0.57*	0.67*	0.57*	–0.35	–0.53*	–0.68*	–0.77*	–0.66*	–0.63*	–0.75*	–0.69*	–0.78*	–0.66*	–0.14	–
W(<0.25)	–0.69*	–0.74*	–0.39	0.64*	0.79*	0.67*	0.73*	–0.27	–0.59*	–0.75*	–0.57*	–0.17	–0.56*	–0.57*	–0.52*	–0.79*	–0.49	0.03	0.42

Note: see Table 11.

Table 13
Empirical correlation coefficients between the content of soil organic matter, the content of sand, silt, clay, the content of aggregates and the content of water-stable aggregates in ordinary chernozem on slopes of southern exposure (n = 15)

Content	SOM	Sa	Si	Cl	D(>10)	D(7-10)	D(5-7)	D(3-5)	D(2-3)	D(1-2)	D(<1)	D(<0.5)	D(<0.25)	W(>5)	W(3-5)	W(2-3)	W(1-2)	W(<1)	W(<0.5)
Sa	0.99*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Si	–0.92*	–0.91*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cl	–0.95*	–0.96*	0.89*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(>10)	–0.54*	–0.50	0.58*	0.50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(7–10)	–0.74*	–0.72*	0.80*	0.72*	0.86*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(5–7)	–0.41	–0.40	0.60*	0.34	0.55*	0.43	–	–	–	–	–	–	–	–	–	–	–	–	–
D(3–5)	0.17	0.14	–0.23	–0.20	–0.32	–0.56*	0.11	–	–	–	–	–	–	–	–	–	–	–	–
D(2–3)	0.71*	0.71*	–0.57*	–0.66*	–0.33	–0.60*	0.17	0.40	–	–	–	–	–	–	–	–	–	–	–
D(1–2)	0.87*	0.88*	–0.77*	–0.79*	–0.53*	–0.79*	–0.13	0.42	0.90*	–	–	–	–	–	–	–	–	–	–
D(0.5–1)	0.92*	0.93*	–0.82*	–0.85*	–0.43	–0.68*	–0.34	0.30	0.78*	0.90*	–	–	–	–	–	–	–	–	–
D(0.25–0.5)	0.96*	0.98*	–0.89*	–0.89*	–0.42	–0.67*	–0.42	0.16	0.69*	0.88*	0.96*	–	–	–	–	–	–	–	–
D(<0.25)	–0.46	–0.47	0.39	0.56*	0.47	0.47	0.25	–0.30	–0.43	–0.40	–0.58*	–0.40	–	–	–	–	–	–	–
W(>5)	0.81*	0.78*	–0.80*	–0.81*	–0.57*	–0.83*	–0.22	0.69*	0.71*	0.83*	0.80*	0.75*	–0.48	–	–	–	–	–	–
W(3–5)	0.94*	0.96*	–0.83*	–0.94*	–0.37	–0.59*	–0.36	0.05	0.58*	0.78*	0.87*	0.94*	–0.42	0.70*	–	–	–	–	–
W(2–3)	0.95*	0.93*	–0.93*	–0.98*	–0.60*	–0.81*	–0.43	0.34	0.63*	0.80*	0.85*	0.88*	–0.57*	0.89*	0.90*	–	–	–	–
W(1–2)	0.90*	0.89*	–0.97*	–0.91*	–0.53*	–0.78*	–0.55*	0.33	0.57*	0.73*	0.83*	0.86*	–0.52*	0.84*	0.83*	0.95*	–	–	–
W(0.5–1)	0.65*	0.63*	–0.71*	–0.71*	–0.51	–0.81*	–0.17	0.77*	0.54*	0.67*	0.59*	0.58*	–0.36	0.94*	0.57*	0.81*	0.78*	–	–
W(0.25–0.5)	–0.59*	–0.62*	0.67*	0.69*	0.01	0.29	0.25	0.21	–0.23	–0.33	–0.39	–0.57*	0.04	–0.33	–0.67*	–0.61*	–0.65*	–0.38	–
W(<0.25)	–0.76*	–0.76*	0.61*	0.69*	0.19	0.29	0.23	0.05	–0.69*	–0.64*	–0.82*	–0.76*	0.57*	–0.51	–0.70*	–0.64*	–0.63*	–0.23	0.31

Note: see Table 11.

Table 14
Empirical correlation coefficients between the content of soil organic matter, the content of sand, silt, clay,
the content of aggregates and the content of water-stable aggregates in luvic chernozem on slopes of southern exposure (n = 15)

Content	SOM	Sa	Si	Cl	D(>10)	D(7-10)	D(5-7)	D(3-5)	D(2-3)	D(1-2)	D(0.5-1)	D(<0.5)	D(<0.25)	W(>5)	W(3-5)	W(2-3)	W(1-2)	W(<1)	W(<0.5)
Sa	0.95*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Si	0.74*	0.62*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cl	–0.93*	–0.87*	–0.77*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(>10)	–0.48	–0.37	–0.53*	0.54*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(7–10)	–0.49	–0.46	–0.35	0.44	0.57*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D(5–7)	–0.26	–0.42	0.12	0.11	–0.25	–0.03	–	–	–	–	–	–	–	–	–	–	–	–	–
D(3–5)	–0.08	–0.14	0.41	–0.12	–0.38	–0.32	0.47	–	–	–	–	–	–	–	–	–	–	–	–
D(2–3)	–0.49	–0.51	–0.18	0.54*	0.01	0.33	0.07	0.10	–	–	–	–	–	–	–	–	–	–	–
D(1–2)	0.43	0.42	–0.01	–0.17	0.11	–0.26	–0.37	–0.69*	–0.10	–	–	–	–	–	–	–	–	–	–
D(0.5–1)	0.71*	0.69*	0.35	–0.50	–0.04	–0.19	–0.59*	–0.55*	–0.17	0.82*	–	–	–	–	–	–	–	–	–
D(0.25–0.5)	0.90*	0.81*	0.72*	–0.81*	–0.22	–0.20	–0.20	–0.23	–0.42	0.50	0.80*	–	–	–	–	–	–	–	–
D(<0.25)	0.09	–0.02	–0.07	0.07	–0.44	–0.25	0.17	–0.39	0.31	0.55*	0.32	0.09	–	–	–	–	–	–	–
W(>5)	0.95*	0.89*	0.70*	–0.85*	–0.48	–0.37	–0.32	–0.18	–0.28	0.53*	0.81*	0.88*	0.22	–	–	–	–	–	–
W(3–5)	0.89*	0.88*	0.49	–0.71*	–0.28	–0.44	–0.54*	–0.39	–0.31	0.73*	0.92*	0.82*	0.27	0.92*	–	–	–	–	–
W(2–3)	0.93*	0.89*	0.64*	–0.78*	–0.43	–0.47	–0.41	–0.22	–0.23	0.64*	0.86*	0.85*	0.29	0.97*	0.97*	–	–	–	–
W(1–2)	0.86*	0.87*	0.49	–0.85*	–0.54*	–0.43	–0.29	–0.15	–0.65*	0.22	0.47	0.65*	0.03	0.77*	0.72*	0.72*	–	–	–
W(0.5–1)	0.25	0.18	0.04	–0.27	–0.36	0.12	0.24	–0.41	–0.30	0.03	0.03	0.25	0.41	0.20	0.12	0.11	0.50	–	–
W(0.25–0.5)	–0.22	–0.15	–0.20	0.03	0.03	0.08	0.17	0.31	–0.35	–0.46	–0.53*	–0.39	–0.51	–0.27	–0.42	–0.40	0.07	–0.11	–
W(<0.25)	–0.78*	–0.72*	–0.62*	0.68*	0.33	0.69*	0.00	–0.06	0.35	–0.47	–0.51	–0.69*	–0.15	–0.67*	–0.71*	–0.74*	–0.53*	–0.07	0.42

Note: see Table 11.

Discussion

The aggregate composition of soils is an important characteristic which largely determines the resistance of soils to erosion (Jiang et al., 2023). As a result of the research, it was established that the top layer of 0–20 cm of ordinary (calcic) chernozems is characterized by an increased content of aggregates of fractions > 10, 7–10, 5–7 mm and a lower content of aggregates of fractions 2–3, 1–2, 0.5–1.0 mm compared to luvic chernozems. A significant influence of forest vegetation on changes in the content of most fractions of aggregates in chernozems was revealed. Changes in the aggregate composition of soils under different types of vegetation are noted by Dou et al. (2020), Gorban (2021). A significant influence of the characteristics of the slopes of northern and southern exposure on the content of aggregates of fractions 0.5–1.0 and 0.25–0.50 mm in ordinary chernozems and on the content of aggregates of fractions > 10, 5–7, 3–5 and 2–3 mm in luvic chernozems has been established. The influence of slope features on the aggregate composition of soils is confirmed in the work of Dong et al. (2022). The results of cluster analysis revealed that in the studied chernozems, aggregates of fractions 5–10, 3–5 and 0.25–2.00 mm are formed under the influence of various factors.

Water-stable aggregates reflect the ability of soils to resist the occurrence of water erosion (Duan et al., 2021). It has been established that the top layer of 0–20 cm of ordinary chernozems is characterized by an increased content of water-stable aggregates of fractions 3–5, 2–3, 1–2 mm and a lower content of water-stable aggregates of fractions > 5, 0.5–1.0, 0.25–0.50 mm compared to luvic chernozems. Changes in the content of water-stable aggregates in the soil as a result of the influence of a change in vegetation type are considered in the work of Wang et al. (2023b). A significant influence of forest vegetation and features of slopes of northern and southern exposure on the content of water-stable aggregates in chernozems was revealed. The results of cluster analysis indicate that in the studied soils, water-stable aggregates of fractions 1–5 mm and 0.25–1.00 mm are formed under the influence of various factors.

Soil organic matter has a significant influence on the physical, chemical and biological properties of soils (Wang et al., 2023a). The influence of forest vegetation led to an increased content of soil organic matter in luvic chernozems compared to ordinary chernozems under conditions of slopes of northern and southern exposure, which may also be due to the location of luvic chernozems on the lower part of the slope compared to ordinary chernozems (Sarapatka et al., 2018). Increased organic matter content in soils under forest compared to soils of other land use types was also found by Han et al. (2023). In ordinary chernozems, the average content of soil organic matter is practically the same under conditions of slopes of northern and southern exposures. The influence of the specific conditions of a slope with a northern exposure contributes to a decrease in the content of soil organic matter in luvic chernozem compared to luvic chernozem on a slope of southern exposure, which can be explained by the presence of a higher clay content (Zheng et al., 2023). Some researchers have found opposite trends – increased organic matter content in forest soils on a northern slope compared to forest soils on a southern slope (Liu et al., 2021), which can be explained by the characteristics of the soils and forest vegetation that were studied. The results of analysis of variance confirm the significant influence of the features of slope exposures on the content of soil organic matter in luvic chernozems, as well as the reliable influence of forest vegetation on the content of organic matter in chernozems, which can be explained by the protective role of the forest, which protects the soil from degradation (Yakovenko et al., 2024), limiting the loss of soil organic matter (Dong et al., 2022) and the reduction of upper soil horizons (Wiśniewski & Märker, 2019).

Particle size distribution largely determines most soil properties and regimes (Lou et al., 2022) and is also a good indicator of soil change due to forest vegetation (Guan et al., 2023; Gorban & Huslystyi, 2023). The influence of forest vegetation in conditions of a slope with a northern exposure caused an increased content of sand and silt and a decreased content of clay in luvic chernozem com-pared to ordinary chernozem. Similar features in the distribution of soil particles under the influence of forest vegetation were established by Moradikeia et al. (2023). Under the conditions of a slope with a southern exposure, the influence of forest vegetation is manifested in an increased clay content and a reduced silt content in luvic chernozem compared to ordinary chernozem. An increase in soil clay content under the influence of forest vegetation was also noted by Guan et al. (2023). The influence of the features of the exposure is manifested in the fact that ordinary chernozem on a slope of northern exposure is characterized by an increased content of clay and a reduced content of silt compared to ordinary chernozem on a slope of southern exposure. Luvic chernozem on a slope with a northern exposure is characterized by a higher content of sand and silt and a lower content of clay compared to luvic chernozem on a slope with a southern exposure. The influence of slope exposure features on soil texture is confirmed by the results of studies by Hu et al. (2023). The results of cluster analysis of data from granulometric analysis of the studied chernozems indicate that the content of sand and clay in ordinary chernozems and luvic chernozems on the slopes of northern and southern exposure is determined by the action of various factors. Similar conclusions about the influence of slope characteristics of different exposures on soils were obtained by Habtamu et al. (2023). The results of variance analysis indicate a significant influence of slope exposure features on the content of silt and clay in ordinary chernozems, sand, silt and clay in luvic chernozems, which can be explained by the different intensity of erosion processes in soils under different types of vegetation (Wang et al., 2023b). Analysis of variance also confirmed the significant influence of forest vegetation on the content of sand and silt in chernozems.

Correlation analysis revealed that the content of soil organic matter has a more pronounced effect on the aggregate composition and content of water-stable aggregates in chernozems compared to the granulometric composition. Xiao et al. (2021) also considers soil organic matter content to be one of the main factors that determines the water stability of soil aggregates. Changes in the aggregate composition of soils by 40.8% are due to changes in the content of soil organic matter and by 20.9% changes in the granulometric composition. Changes in the content of water-stable aggregates by 60.5% were caused by changes in the content of soil organic matter and by 8.8% by changes in particle size distribution. The existence of close direct relationships was revealed between the content of soil organic matter and the content of aggregates of the 0.5–1.0 mm fraction (r = 0.71–0.92), as well as between the content of soil organic matter and the content of water-stable aggregates of the 3–5 mm fraction (r = 0.89–0.97), 2–3 mm (r = 0.86–0.96), 1–2 mm (r = 0.78–0.90) in all studied chernozems. Zhu et al. (2017) note that the greatest differences between soils of different types of land use were found in the content of aggregates of fractions 2–5, 1–2, 0.25 mm. This indicates a greater indicator value of aggregates of fractions < 2 mm compared to aggregates of fractions >2 mm (Luo et al., 2023). The existence of close direct relationships between the sand content and the content of water-stable aggregates of the 3–5 mm (r = 0.74–0.96) and 2–3 mm (r = 0.70–0.93) fractions has been established. It was revealed that closer connections between the content of soil organic matter and granulometric composition with aggregate composition and the content of water-stable aggregates are characteristic of ordinary chernozems compared to luvic chernozems.

Conclusion

The influence of forest ecosystems on the aggregate composition of chernozems is manifested in an increase in the content of aggregates of fractions 2–3, 1–2 and 0.5–1.0 mm, as well as water-stable aggregates of fractions >5, 0.5–1.0 and 0.25–0.50 mm in the 0–20 cm layer. It has been established that the content of soil organic matter determines the aggregate composition by 40.8% and the content of water-stable aggregates by 60.5%, and the characteristics of the granulometric composition – by 20.9% and 8.8%, respectively. The existence of close direct relationships was revealed between the content of soil organic matter and the content of aggregates of the 0.5–1.0 mm fraction (r = 0.71–0.92), as well as between the content of soil organic matter and the content of water-stable aggregates of the 3–5 mm fraction (r = 0.89–0.97), 2–3 mm (r = 0.86–0.96), 1–2 mm (r = 0.78–0.90) in all studied chernozems. The existence of close direct relationships between the sand content and the content of water-stable aggregates of the 3–5 mm (r = 0.74–0.96) and 2–3 mm (r = 0.70–0.93) fractions has been established. An increase in the content of soil organic matter and sand content in soils under the influence of forest ecosystems helps to improve the aggregate composition and increase the content of water-stable aggregates. This ensures increased resistance of soils in forest ecosystems to various negative factors, such as desertification, degradation, wind and water erosion.

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References

Bamutaze, Y., Meadows, M. E., Mwanjalolo, M., & Musinguzi, P. (2021). Effect of land use systems and topographical attributes on the condition of surface soil physicochemical properties in a highland catchment of the Lake Victoria Basin, Uganda. Catena, 203, 105343.

Belova, N. A., & Travleev, A. P. (1999). Estestvennye lesa i stepnye pochvy (ekolohiya, mykromorfolohiya, henezys) [Natural forest and steppe soils (ecology, micromorphology, genesis)]. Dnepropetrovsk University Press, Dnepropetrovsk (in Russian).

Bozhko, K., & Bilova, N. (2020). The influence of the slope exposure on the soil aggregation and structure, water stability of aggregates, and ecological microstructure formation of the ravine forest soils in Pre-Dnipro Region (Ukraine). Ekológia (Bratislava), 39(2), 116–129.

Carter, M. R., & Gregorich, E. G. (Eds.). (2008). Soil sampling and methods of analysis. CRC Press, Boca Raton.

Chen, L., Li, Y., & Zhang, Z. (2023). Impact of land use type and slope position on the erodibility of karst hillslopes in Southwest China. Catena, 233, 107498.

Ding, H., Zhu, H., Sun, R., Wen, W., & Bi, R. (2024). Variation in the physical properties of soil in relation to natural and anthropogenic factors in the hilly loess region of China. Catena, 236, 107751.

Dong, L., Li, J., Zhang, Y., Bing, M., Liu, Y., Wu, J., Hai, X., Li, A., Wang, K., Wu, P., Shangguan, Z., & Deng, L. (2022). Effects of vegetation restoration types on soil nutrients and soil erodibility regulated by slope positions on the Loess Plateau. Journal of Environmental Management, 302, 113985.

Dou, Y., Yang, Y., An, S., & Zhu, Z. (2020). Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. Catena, 185, 104294.

Duan, L., Sheng, H., Yuan, H., Zhou, Q., & Li, Z. (2021). Land use conversion and lithology impacts soil aggregate stability in subtropical China. Geoderma, 389, 114953.

Eckmeier, E., Gerlach, R., Gehrt, E., & Schmidt, M. W. I. (2007). Pedogenesis of Chernozems in Central Europe – A review. Geoderma, 139(3–4), 288–299.

Gao, Y., & Yang, P. (2023). Temporal and spatial distribution of soil water repellency in grassland soils and its relation to soil moisture, hydrophobic matter, and particle size. Science of the Total Environment, 904, 166700.

Gorban, V. (2021). *Robinia pseudoacacia* and *Quercus robur* plantations change the physical properties of calcic chernozem. In: Dmytruk, Y., & Dent, D. (Eds.). Soils under stress. Springer, Cham. Pp. 95–103.

Gorban, V., & Huslystyi, A. (2023). Changes in selected properties of calcic chernozem due to cultivation of *Robinia pseudoacacia* and *Quercus robur*. Folia Oecologica, 50(2), 196–203.

Gou, Y., Chen, H., Wu, W., & Liu, H.-B. (2015). Effects of slope position, aspect and cropping system on soil nutrient variability in hilly areas. Soil Research, 53(3), 338.

Guan, X., Wang, J., Liu, G., Xiao, M., Ding, Y., & Chen, J. (2023). Grain size characteristics of surface sediment in the Jilantai Salt Lake Protection System after long-term wind-sand activities. Land Degradation and Development, 35(1), 321–333.

Guo, M., Chen, Z., Wang, W., Wang, T., Wang, W., & Cui, Z. (2021). Revegetation induced change in soil erodibility as influenced by slope situation on the Loess Plateau. Science of the Total Environment, 772, 145540.

Habtamu, M., Elias, E., Argaw, M., & Bulley, H. N. (2023). Effects of land use and landscape position on soil properties in Dire Watershed, Central Highlands of Ethiopia. Eurasian Soil Science, 56(7), 951–962.

Han, Y., Wang, Q., Li, F., Guo, Y., & Zheng, Y. (2023). Effects of types of farmland returning to forest on the dynamics of soil aggregate and organic carbon in Upper Reaches of Minjiang River. Guangdong Agricultural Sciences, 50(4), 84–92.

Hu, J., Huang, Z., Li, S., Liu, B., & Ci, E. (2023). Assessing profile uniformity of soils from weathered clastic sedimentary rocks in southwest China. Catena, 224, 107007.

Jiang, W., Li, Z., Xie, H., Ouyang, K., Yuan, H., & Duan, L. (2023). Land use change impacts on red slate soil aggregates and associated organic carbon in diverse soil layers in subtropical China. Science of the Total Environment, 856, 159194.

Kobza, J., & Pálka, B. (2022). Black soils outSIDE of the INBS criteria in Slovakia. Polish Journal of Soil Science, 55(2), 67–77.

Łabaz, B., Kabała, C., Dudek, M., & Waroszewski, J. (2019). Morphological diversity of chernozemic soils in South-Western Poland. Soil Science Annual, 70(3), 211–224.

Labaz, B., Kabala, C., Waroszewski, J., Dudek, M., Bogacz, A., Gruszka, D., & Mlynek, S. (2022). Medium-term transformation of chernozems under broadleaf forests in the temperate climate of south-east Poland. Geoderma Regional, 30, e00535.

Lasota, J., Błońska, E., Łyszczarz, S., & Sadowy, A. (2019). Forest habitats and forest types on chernozems in South-Eastern Poland. Soil Science Annual, 70(3), 234–243.

Le Bissonnais, Y., Prieto, I., Roumet, C., Nespoulous, J., Metayer, J., Huon, S., Villatoro, M., & Stokes, A. (2017). Soil aggregate stability in Mediterranean and tropical agro-ecosystems: Effect of plant roots and soil characteristics. Plant and Soil, 424(1–2), 303–317.

Li, C., Cao, Z., Chang, J., Zhang, Y., Zhu, G., Zong, N., He, Y., Zhang, J., & He, N. (2017). Elevational gradient affect functional fractions of soil organic carbon and aggregates stability in a Tibetan alpine meadow. Catena, 156, 139–148.

Liang, P., Wang, X., Xu, Q., Zhang, J., Fang, R., Fu, Z., & Chen, H. (2023). Lithology-mediated soil erodibility characteristics after vegetation restoration in the karst region of Southwest China. Land Degradation and Development, 35(3), 1074–1086.

Liu, X., Jia, G., & Yu, X. (2021). Effects of the undecomposed layer and semi-decomposed layer of *Quercus variabilis* litter on the soil erosion process and the eroded sediment particle size distribution. Hydrological Processes, 35(5), e14195.

Lou, B., Wang, Y., Zhou, N., Yan, J., & Askar, A. (2022). Soil particle size composition characteristics of *Pinus sylvestris* plantations in Nur-Sultan City. Arid Land Geography, 45(1), 219–225.

Luo, T., Xia, L., Xia, D., Liu, W., Xu, Y., He, Z., & Xu, W. (2023). Impact of typical land use type on the stability and content of carbon and nitrogen of soil aggregates in Western Hubei. Ecosphere, 14(12), e4736.

Moradikeia, N., Esmali Ouri, A., Asghari, S., & Golshan, M. (2023). Comparing runoff and sediment production in three land use in Fandoghlu Area, Ardabil Province. Journal of Water and Health, 49(1), 1007394.

Ponomarenko, O. M., Nykyforov, V. V., & Yakovenko, V. M. (2022). Changes of chemical and micromorphological properties of Poltava region soils of Ukraine for the last 130 years. Ukrainian Geographical Journal, 1, 18–26.

Sarapatka, B., Cap, L., & Bila, P. (2018). The varying effect of water erosion on chemical and biochemical soil properties in different parts of chernozem slopes. Geoderma, 314, 20–26.

Strouhalová, B., Ertlen, D., Šefrna, L., Novák, T. J., Virágh, K., & Schwartz, D. (2019). Assessing the vegetation history of european chernozems through quailtative near infrared spectroscopy. Quaternaire, 30(3), 227–241.

Thiele-Bruhn, S., Leinweber, P., Eckhardt, K.-U., Siem, H. K., & Blume, H.-P. (2014). Chernozem properties of black soils in the Baltic Region of Germany as revealed by mass-spectrometric fingerprinting of organic matter. Geoderma, 213, 144–154.

Travleev, A. P. (1996). Forest soil science and steppe forest science. Eurasian Soil Science, 29(4), 390–394.

Vysloužilová, B., Danková, L., Ertlen, D., Novák, J., Schwartz, D., Šefrna, L., Delhon, C., & Berger, J.-F. (2014). Vegetation history of chernozems in the Czech Republic. Vegetation History and Archaeobotany, 23(S1), 97–108.

Wang, H., Wang, J., & Zhang, G. (2021). Impact of landscape positions on soil erodibility indices in typical vegetation-restored slope-gully systems on the Loess Plateau of China. Catena, 201, 105235.

Wang, S., Zhuang, Q., Zhou, M., Jin, X., Yu, N., & Yuan, T. (2023a). Temporal and spatial changes in soil organic carbon and soil inorganic carbon stocks in the semi-arid area of northeast China. Ecological Indicators, 146, 109776.

Wang, Y., Wang, J., Shi, W., & Li, Z. (2023b). Effects of microtopography shaping on characteristics of eroded sediment particles of a dump slope in an opencast coal mine in China. Land Degradation and Development, 35(4), 1411–1424.

Wiśniewski, P., & Märker, M. (2019). The role of soil-protecting forests in reducing soil erosion in young glacial landscapes of Northern-Central Poland. Geoderma, 337, 1227–1235.

Xiao, L., Huang, Y., Zhao, J., Zhou, J., & Abbas, F. (2021). Effects of planting structure on soil water-stable aggregates, microbial biomass and enzyme activity in a catchment of Loess Plateau terraces, China. Applied Soil Ecology, 159, 103819.

Yakovenko, V. (2017). Fractal properties of coarse/fine-related distribution in forest soils on colluvium. In: Dent, D., & Dmytruk, Y. (Eds.). Soil science working for a living. Springer, Cham. Pp. 29–42.

Yakovenko, V., Gorban, V., Kotovych, O., Didur, O., & Lisovets, O. (2024). Visual evaluation of soil structure in low-intensity land use systems of steppe zone of Ukraine. Soil Use and Management, 40(1), e12972.

Yang, J., Xin, X., Zhang, X., Zhong, X., Yang, W., Ren, G., & Zhu, A. (2023). Effects of soil physical and chemical properties on phosphorus adsorption-desorption in fluvo-aquic soil under conservation tillage. Soil and Tillage Research, 234, 105840.

Yang, Y., Wei, H., Lin, L., Deng, Y., & Duan, X. (2024). Effect of vegetation restoration on soil humus and aggregate stability within the Karst Region of southwest China. Forests, 15(2), 292.

Zheng, Y., Wang, Y., Zhang, Y., Zhang, J., Wang, Y., & Zhu, J. (2023). Broadleaf trees increase soil aggregate stability in mixed forest stands of southwest China. Forests, 14(12), 2402.

Zhu, G., Shangguan, Z., & Deng, L. (2017). Soil aggregate stability and aggregate-associated carbon and nitrogen in natural restoration grassland and Chinese red pine plantation on the Loess Plateau. Catena, 149, 253–260.