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Visual evaluation of soil structure in low-intensity land use systems of steppe zone of Ukraine

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Abstract

The network of natural forests and shelterbelts is a crucial element of agroforestry systems for the efficient and environmentally sustainable land use in Ukraine. From 2016 to 2021, we studied the quality of black soils structure under steppe wildland herbaceous vegetation, man-made tree plantations of *Robinia pseudoacacia* L. and *Quercus robur* L., and native forest vegetation of ravines and floodplains in the steppe zone of Ukraine. According to the visual evaluation of soil structure (VESS) scores, the content of the agronomically valuable fraction (AVF), soil organic carbon (SOC) and earthworm casts, native forest soils (Chernozems and Phaeozems) had a significantly ($p < .05$) higher soil structural quality in 0–25 cm layer as compared with the Chernozems under the steppe vegetation and shelterbelt plantations. In the conditions of steppe landscapes, VESS methods were shown to provide efficient diagnostics to differentiate the black soil structural quality of low-intensity land use systems, that is steppe wildlands, shelterbelts, native forests: VESS indicators significantly ($p < .05$) correlated with quantitative characteristics of soil structure. The most significant dependence was found between VESS parameters and earthworm casts content. The need to improve VESS method was demonstrated, that is to assign higher weight to the earthworm bioturbation process as one of the key indicators of soil structural quality.

KEYWORDS

agroforestry systems, black soils, earthworm bioturbation, quantitative characteristics of soil structure, shelterbelt plantations, soil quality, VESS

1 | INTRODUCTION

The steppe zone of Ukraine is an important region in world agricultural production, in particular for the cultivation of cereals and oilseeds. Intensive land management, however, causes nutrient losses and impairs the physical and structural properties of soils of the steppe landscapes of Ukraine (Baliuk et al., 2021; Medvedev et al., 2014; Ponomarenko et al., 2022). Introduction and improvement of agroforestry techniques were demonstrated to be efficient strategies to counteract soil degradation, as they enable creation of an environmentally sustainable land use system based on the integration of natural forests into the agricultural landscape; they usually involve the creation of man-made forest plantations having various functional purposes (Pantera et al., 2021; Plieninger et al., 2020; Rolo et al., 2023). As a result of intensive agricultural use of lands in the steppe zone, natural steppe herbaceous vegetation has been preserved only on territories designated for conservation and protection of natural environments and, fragmentarily, in small areas inconvenient for agriculture. Natural forests are found in those areas of the steppe landscape that receive supplementary moisture in addition to atmospheric precipitation, that is floodplains and ravines. In those landscapes, natural forests of similar species composition and structure are formed (Belgard, 1950). Numerous man-made tree plantations of different species had been created in Ukraine in the form of massifs and belts among agricultural areas, on the slopes of ravines, river banks and along highways and railways. Due to their functional purpose, shelterbelts or windbreaks have become major man-made plantations in the steppe zone (Yukhnovskyi et al., 2021). It should be noted that the Russian military invasion of Ukraine in February 2022 led to the destruction or damage of large areas of natural and shelterbelt plantations in the southern and eastern regions of the steppe zone of Ukraine, with subsequent deterioration of agroforestry systems and further negative environmental impact.

Soil quality indicators of low-intensity land use systems are the reference indicators for monitoring changes and controlling the quality of soils subjected to intensive agricultural use. Land use and management practices significantly affect the quality of soil structure (Bai et al., 2018; Ball et al., 2007), which comprises a universal indicator of soil quality in general (Bünemann et al., 2018; Mueller et al., 2010; Rabot et al., 2018). A quick and comprehensive characterization of soil quality can be provided by visual structure assessment methods (Ball et al., 2016; Emmet-Booth et al., 2016), which statistically correlate with physical and chemical soil properties (Çelik et al., 2020; Cherubin et al., 2018; Guimarães et al., 2013; Lin et al., 2022; Mutuku et al., 2021). A correlation of visual assessments with biological activity has also been established (Cavalieri-Polizeli et al., 2022; Demétrio et al., 2022); however, there are no statistical studies of the relationship between VESS scores and earthworm casts content, as the most accurate indicator of earthworm bioturbation. Currently, the methods of visual evaluation of soil (VESS) and subsoil (SubVESS) structure are being validated in different natural zones of the world, and mainly in the systems characterized by contrast land use with intensive agricultural impact on soils (arable lands, orchards, pastures) (Franco et al., 2019; Olivares et al., 2023). To our knowledge, the present work is the first application of VESS and SubVESS methods for the study of soils in the steppe zone of Ukraine. Accordingly, the aims of this study were (i) to determine the black soil's structure quality of low-intensity land use systems of herbaceous steppe wildlands, shelterbelts and natural forests, (ii) to assess the efficacy of VESS scores as the indicators of soil quality of low-intensity land use systems, and (iii) to relate VESS scores to quantitative structure characteristics, i.e. content of agronomically valuable fraction (AVF), soil organic carbon (SOC) and earthworm casts content. This paper specifically evaluates the earthworm casts content as an indicator of structure quality, since earthworm bioturbation is the leading factor in the structure formation of surface soil horizons in low-intensity land use systems (Blouin et al., 2013; Piron et al., 2017).

2 | MATERIALS AND METHODS

2.1 | Study area

The research was conducted in the basin of the Samara River (left tributary of the Dnipro River) in Novomoskovsk district of the Dnipropetrovsk region of Ukraine. The study area covers the left-bank floodplain portion of the Samara River valley and the right-bank plateau north of the riverbed where erosive landforms (ravines, gullies) are abundant. Within the study area, dry east winds dominate. All this determines continental and dry climate (Buksha et al., 2021). The average annual temperature is +8.2°C with minimum of −38°C and maximum of +37°C. The average annual rainfall in the region is 508 mm (Gritsan, 2000). Soils on the plateau are humidified exclusively by atmospheric precipitations. The study sites represented three land use modes: steppe wildlands with natural herbaceous vegetation; shelterbelts; native ravine and floodplain forests (Figure 1):

Site 1 (48°45′37.9′′ N, 35°27′40.1′′ E 103 m asl): Soil is a Calcic Chernozem (Siltic, Tonguic) on the watershed steppe landscape; parent material is a loess. Dominant vegetation is composed of: *Festuca valesiaca* Gaudin, *Koeleria cristata* (L.) Pers., *Stipa lessingiana* Trin. et Rupr., *Poa angustifolia* L., *Elytrigia repens* (L.) Nevski, *Medicago romanica* Prod., *Thymus marschallianus* Willd., *Artemisia austriaca* Jacq., *Salvia nemorosa* L., *Linum hirsutum* L., *Achillea submillefolium* Klok. et Krytzka and *Euphorbia stepposa* Zoz ex Prokh.

Site 2 (48°45′27.6′′ N, 35°29′33.4′′ E 127 m asl): Soil is a Calcic Chernozem (Siltic, Tonguic) on the watershed steppe landscape; parent material is a loess. Dominant vegetation is represented by man-made linear tree plantations of *Robinia pseudoacacia* L. about 60 years of age. The distance between the trees in a row is 0.5 m and 1 m between rows. Herbaceous cover of the plantation is predominantly composed of *Elytrigia repens*, *Poa angustifolia*, *Calamagrostis epigeios* (L.) Roth, *Chelidonium majus* L. and *Ballota nigra* L.

Site 3 (48°45′22.5′′ N, 035°30′13.38′′ E 150 m asl): Soil is a Calcic Chernozem (Siltic, Tonguic) on the watershed

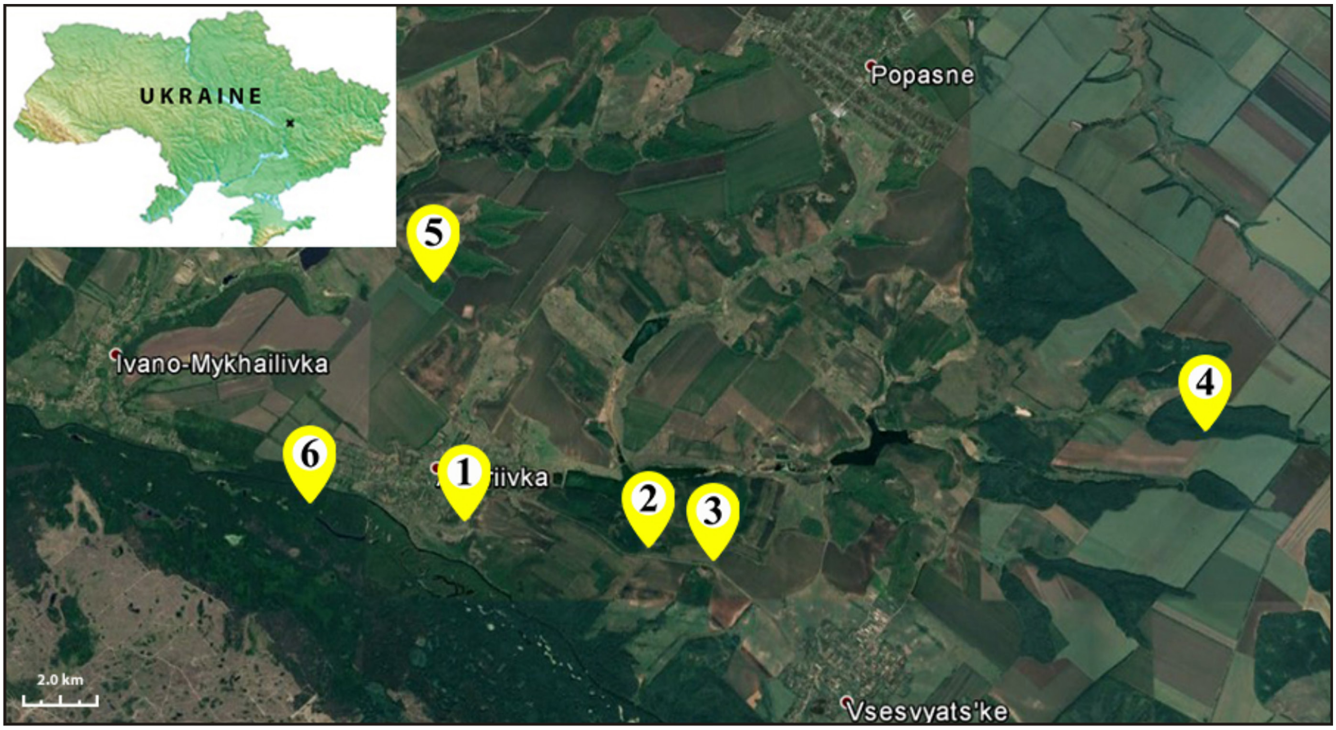

FIGURE 1 Study area and site locations: 1—steppe wildland on plateau, 2—*Robinia pseudoacacia* shelterbelt plantation on plateau, 3—*Quercus robur* shelterbelt plantation on plateau, 4—native forest on ravine slope, 5—native forest at ravine bottom, 6—native forest in floodplain.

steppe landscape; parent material is a loess. Dominant vegetation is represented by linear tree plantations of about 60 years of age. The rows of *Quercus robur* are intermitted by the rows of *Acer tataricum* L.; occasionally, *Euonymus europaea* L. is found. Distance between the trees in a row is 0.75 m and 1.5 m between the rows. Herbaceous cover was predominantly composed of *Elytrigia repens*, *Poa compressa* L., *Poa angustifolia*, *Brachypodium sylvaticum* (Huds.) P. Beauv., *Lathyrus tuberosus* L., *Salvia verticillata* L., *Daucus carota* L., *Anthriscus sylvestris (*L.) Hoffm., *Viola hirta* L., *Geum urbanum* L. and *Convallaria majalis* L.

Site 4 (48°46′14.8′′ N, 35°35′19.5′′ E 149 m asl): Soil is a Luvic Chernozem (Hyperhumic, Pachic, Siltic) on the middle ravine slope (slope angle 7°, aspect N). Parent material is a loess. Natural forest was primarily formed by *Quercus robur*, *Acer platanoides* L., *Fraxinus excelsior* L., *Tilia cordata* Mill., with rather abundant *Ulmus minor* Mill., *Euonymus europaea* 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. and *Polygonatum multiflorum* (L.).

Site 5 (48°47′17.5′′ N, 35°27′16.5′′ E 76 m asl): Soil is a Luvic Chernic Phaeozem (Pantocolluvic, Hyperhumic, Pachic, Siltic) on the ravine bottom. Parent material is a humified colluvium. Native forest vegetation predominately contained *Quercus robur*, *Fraxinus excelsior*, *Acer campestre* L., *Ulmus minor*, *Tilia cordata*, *Acer platanoides*. Abundant herbaceous cover was formed by *Stellaria holostea*, *Anthriscus sylvestris*, *Geum urbanum*, *Asarum europaeum*, *Galium aparine*, *Viola odorata*, *Glechoma hederacea*, *Polygonatum multiflorum* and *Urtica dioica* L.

Site 6 (48°45′46.1′′ N, 35°26′03.9′′ E 62 m asl): Soil is a Fluvic Chernic Phaeozem (Hyperhumic, Pachic, Siltic) in a central floodplain of the Samara River. Parent material is a humified alluvium. Native forest vegetation predominately contained *Quercus robur*, *Fraxinus excelsior*, *Ulmus minor*, *Tilia cordata*, *Acer campestre*, *Acer platanoides*, *Acer tataricum* and *Euonymus verrucosa*. Abundant herbaceous cover consisted of *Galium aparine*, *Stellaria holostea*, *Anthriscus sylvestris*, *Asarum europaeum*, *Urtica dioica*, *Viola odorata* and *Glechoma hederacea*.

2.2 | Field and laboratory methods

We made three soil sections at each study site typical for each type of the vegetation. Main soil section (for which geographical coordinates are specified above) was made down to 180 cm deep, and two other sections each were 100 cm deep. Soil genetic horizons were determined according to the FAO guidelines (FAO, 2006). The classification of soils was determined according to the

World reference base for soil resources 2014 (FAO, 2015). The studied soils were formed on parent rocks of different lithology; thus, the soils differ in their composition and depths of genetic profiles (Figure 2). Therefore, the structural quality was determined in the formally selected layers of the profile: 0–25, 25–50, 50–75 and 75–100 cm. The main attention was paid to the surface (0–25 cm) layer, given its higher soil dynamics, and its importance in determining properties and regimens for the entire soil profile. Research was conducted during years 2016 to 2021. The field stage was conducted in June, the period when the soil moisture content was optimal for the sampling. To keep the structural aggregates intact, the samples were placed in boxes made of dense cardboard with the dimensions of 17 × 10 × 7 cm.

2.2.1 | VESS/SubVESS

VESS was performed according to Ball et al. (2007) with the improvements by Guimarães et al. (2011) for the 0–25 cm layer. To determine the VESS scores, soil samples were taken from an undisturbed soil cut using a shovel to a depth of 25 cm; the samples had a thickness of 10 cm and a width of 20 cm. The soil material was then carefully dismantled by hand to determine the characteristics of its structural units (Ball et al., 2007). The main criteria for determining structural quality are size, shape, visible porosity of aggregates, signs of bioturbation activity and the presence of roots. The difficulty of sample extraction, and the presence of larger, more angular and less porous aggregates increased the Sq score (i.e. worsened the structure quality). Based on these criteria, contrasting layers were identified, and each was assigned a VESS score ranging from 1 to 2 (good), 3 (fair) to 4–5 (poor soil structure) using a visual interpretation chart (Guimarães et al., 2011). SubVESS was assessed according to Ball et al. (2015) for the layers of 25–50, 50–75 and 75–100 cm. The criteria for visual evaluation of subsoil structure were sequentially defined for each layer assessments of mottling, strength, porosity, the pattern and depth of root penetration and aggregate size/shape. Based on these, Ssq scores from 1 to 3 (good), 4 (fair) to 5 (poor) were assigned using a visual interpretation chart (Ball et al., 2015). If the layer included more than one genetic horizon, the VESS and SubVESS score were determined as a weighted average based on the determined scores for each of the horizons:

$\mathrm{Sq}_{\mathrm{score}} = \sum_{i=1}^{n} \frac{\mathrm{Sq}_i T_i}{T\,T}$ Where $\mathrm{Sq}_{\mathrm{score}}$ is the overall VESS or SubVESS score of the sample, Sq_i and T_i are the score and the thickness of each identified soil layer, respectively, and TT is the total thickness of soil sample.

2.2.2 | Quantitative characteristics of soil structure

Soil aggregate size distribution was determined for the layers of 0–25, 25–50, 50–75 and 75–100 cm by dry sieving through a set of sieves with mesh sizes of 10, 7, 5, 3, 2, 1, 0.5 and 0.25 mm. Based on aggregate size distribution, the content of 10–0.25 mm fraction was calculated, as it is an agronomically valuable fraction (Medvedev, 2008). Soil organic carbon was determined by the Walkley-Black titration method (FAO, 2019). Briefly, soil organic matter was oxidized by a solution of potassium dichromate ($K_2Cr_2O_7$), followed by quantitative determination of unreacted portion with Mohr's salt ($(NH4)_2SO_4 \cdot FeSO_4 \cdot 6H_2O$). Intensity of earthworm bioturbation was determined by the content of earthworm casts in 0–10 cm surface layer. Aggregates from the fractions of 2–1, 1–0.5 and 0.5–0.25 mm obtained in the analysis of soil aggregate size distribution were randomly selected for the preparation of soil thin sections for subsequent micromorphology analysis (Yakovenko, 2019). Earthworm casts were determined by their characteristic micromorphological features (Stoops et al., 2003); 423–567 aggregates were studied for each experimental site. The average content of earthworm casts was calculated as a percentage of the total aggregate number in the fraction of 2–0.25 mm. Photomicrographs were obtained by UCMOS14000KPA digital camera.

2.2.3 | Statistical analysis

To assess soil characteristics, the experiments were performed in triplicate. All quantitative parameters were processed statistically in Statgraphics Centurion XV Version 15.1.02 package with calculation their means and standard deviations. The differences between mean values were tested by Tukey's HSD and considered statistically significant at $p \leq .05$. Tukey's HSD test was performed using Statgraphics Centurion XV Version 15.1.02 package. The relationships between VESS scores and quantitative characteristics of soil structure were assessed by the Pearson correlation coefficient. Graphical relationship of those indicators was represented by regression equations computed in the Excel Statistical package.

3 | RESULTS

3.1 | VESS/SubVESS evaluation

In the 0–25 cm layer of Chernozems under wildland steppe vegetation and shelterbelt forest vegetation, two

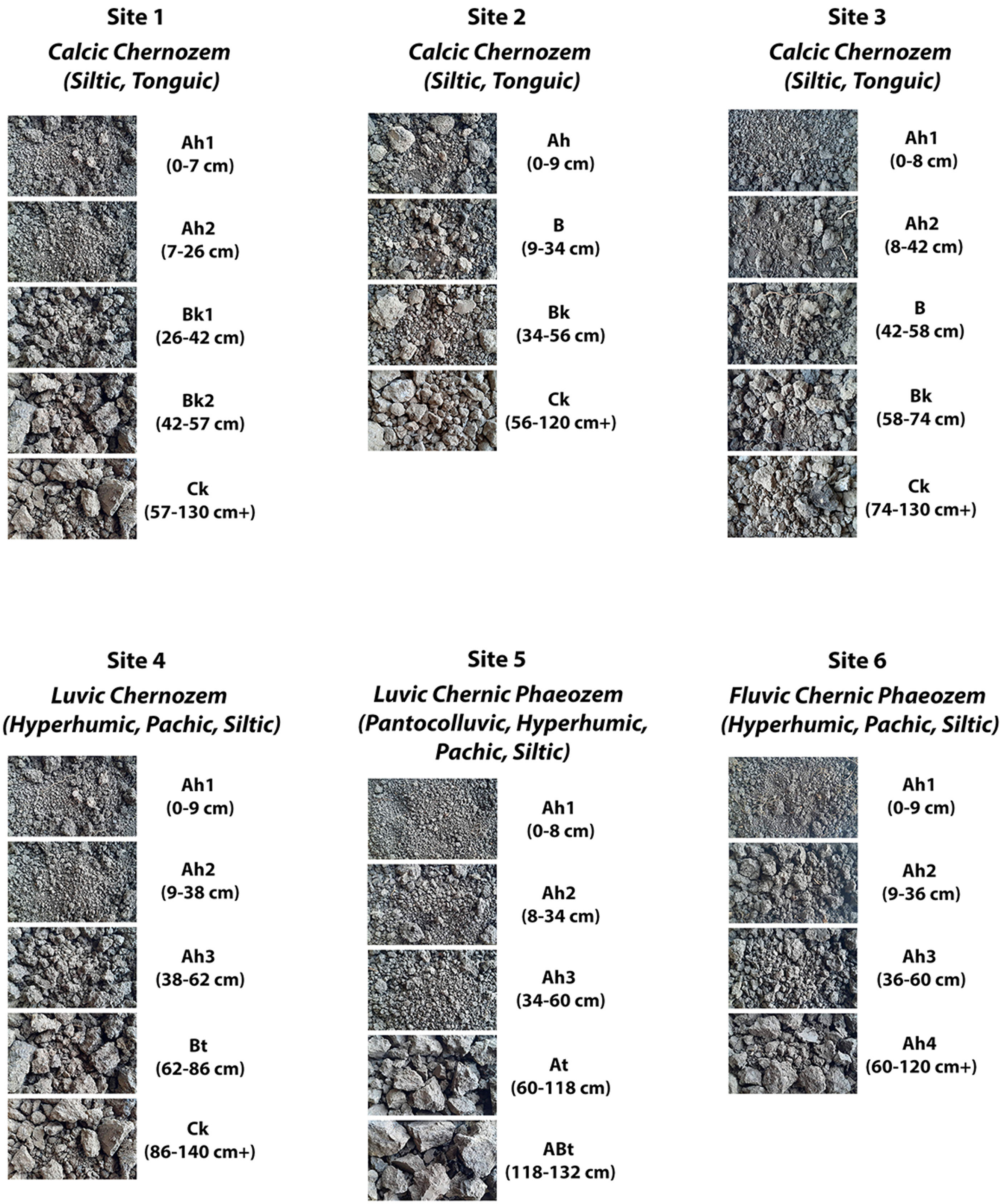

FIGURE 2 Structure of soil genetic horizons under different vegetation types in land use systems of steppe wildland (Site 1), man-made shelterbelt plantations (Site 2, Site 3) and native forest (Site 4, Site 5, Site 6). Vegetation/parent material: Site 1—steppe vegetation on plateau/loess; Site 2—*Robinia pseudoacacia* plantations on plateau/loess; Site 3—*Quercus robur* plantations on plateau/loess; Site 4—native forest on middle ravine slope/loess; Site 5—native forest at ravine bottom/humified colluvium; Site 6—native forest in central floodplain/humified alluvium.

sublayers with different Sq values were distinguished (Figure 3); the weighted average Sq score varied from 1.71 to 1.77 (Table 1). The surface sublayer with a thickness of 4–9 cm, which corresponded to A1 soil genetic horizon (FAO, 2006), was assigned the Sq score of 1 (Figure 3). This sublayer had very loose bulk density and high porosity (the pore types were mainly interstitials and vughs). Roots of herbaceous plants were highly abundant throughout this layer. When examined, material of this layer readily decomposed into small granular and subangular peds and large highly porous subangular blocks which easily disintegrated further into smaller aggregates (Figure 2). The second sublayer with a thickness of 16–21 cm within the layer of 0–25 cm corresponded to the A2 soil genetic horizon and had a Sq score of 2. Compared with the surface layer, its bulk density was increased, the dominant structure type became subangular, sizes of subangular and granular aggregates were higher. The 25–50 cm layer had a SubVESS scores (Ssq) in the range from 2.27 to 2.45; the 50–75 cm layer had a Ssq score of 3.33; the 75–100 cm layer had a Ssq score from 3.33 to 3.67 (Table 1). Down the profile, the morphology of the dominant structure types changed to subangular, angular and prismatic; the sizes of peds increased, along with their bulk density. Bottom 75–100 cm layer had a clear vertical subdivision of its structure, which is typical for loess.

Within the 0–25 cm layer of native forest soils, two sublayers were also distinguished by the quality of their structure; they corresponded to A1 and A2 genetic horizons (Figure 2). The weighted average Sq score of the 0–25 cm layer varied in a narrow range of 1.31–1.34 (Table 1). The first sublayer had a thickness of 7–11 cm (Figure 3) and was primarily characterized by granular vermicular and subangular structures (Figure 2); its Sq value was 1. Also, natural forest soils had higher porosity and lower bulk density compared with soils under shelterbelt plantations and wildland steppe vegetation. Surface sublayer had a high content of herbaceous roots throughout its depth. The second sublayer was characterized by a predominantly subangular structure and a frequent occurrence of granular aggregates (which were typically the earthworms' casts). Aggregates were larger in size compared with those in surface sublayer. The bulk density was higher. According to the set of characteristics and significant biogenic activity (both zoogenic and phytogenic), the quality of this soil according to Sq scores occupied a position between 1 (friable) and 2 (intact), thus we assigned its Sq score to be 1.5. The 25–50 cm layer was characterized by predominance of subangular and significant involvement of granular vermicular structures. There was a significant content of herbaceous roots throughout the full depth of this layer. Accordingly, soil structural quality was determined to be high (Ssq scores 1.73–1.81) (Table 1). The 50–75 cm layer of ravine soils was primarily composed of subangular, angular and prismatic peds. Size of the peds increased with depth; their facets and ribs became more pronounced; bulk density of the soil material increased, while the occurrence of plant roots decreased. The Ssq score of this layer was 2.55–3.23. The lowest 75–100 cm layer was characterized by very high bulk density and very low porosity. The structures were predominantly angular and prismatic. Pores were represented by planes and biogenic channels. Such characteristics led to higher Ssq scores (3.67), that is to lower structural quality of ravine soils. Floodplain soil had the best SubVESS scores at the level of 3.33.

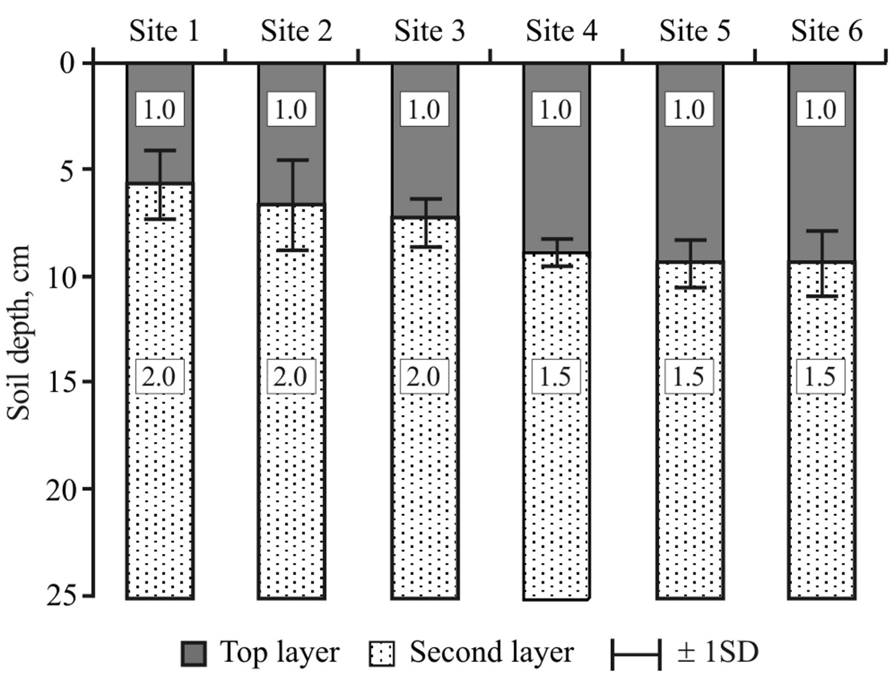

FIGURE 3 VESS scores (Sq) and average thickness of the sublayers contrast in their structural quality within the 0–25 cm surface layer under different types of vegetation. SD—standard deviation for surface sublayer thickness.

TABLE 1 VESS (Sq) scores for surface 0–25 cm layer, and SubVESS (Ssq) scores for 25–50, 50–75 and 75–100 cm layers in soils under different vegetation types (x ± SD, $n = 3$).

	Land use system					
	Wildland	Shelterbelts		Native forest		
Layer, cm	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
0–25	1.77 ± 0.06^{a}	1.73 ± 0.08^{a}	1.71 ± 0.05^{a}	1.33 ± 0.01^{b}	1.31 ± 0.02^{b}	1.31 ± 0.03^{b}
25–50	2.28 ± 0.07^{a}	2.45 ± 0.05^{b}	2.27 ± 0.06^{a}	1.73 ± 0.03^{c}	1.81 ± 0.01^{c}	1.79 ± 0.02^{c}
50–75	3.33 ± 0.58^{a}	3.33 ± 0.58^{a}	3.33 ± 0.58^{a}	3.01 ± 0.12^{a}	3.32 ± 0.27^{a}	2.55 ± 0.06^{a}
75–100	3.67 ± 0.58^{a}	3.67 ± 0.58^{a}	3.33 ± 0.58^{a}	3.67 ± 0.58^{a}	3.67 ± 0.58^{a}	3.33 ± 0.58^{a}

Note: Sq and Ssq scores varied from 1 (good) to 5 (poor soil structure). The different letters indicate statistically significant differences in the means of the compared pair according to the Tukey criterion ($p < 0.05$).

Comparing different Land use systems (Table 1), we note that statistically significantly ($p < .05$) lower VESS scores (higher structure quality) are observed for the 0–25 cm layer of native forest (sites 4–6) compared with wildland and shelterbelts (sites 1–3) (respectively ranked range 1.31–1.33 vs. 1.77–1.71). A similar trend can be observed when comparing the land use system for the 25–50 cm layer, where for native forest (sites 4–6) we observe statistically significantly ($p < .05$) lower VESS scores (higher quality) than for wildland and shelterbelts (sites 1–3) (respectively ranked range 1.73–1.81 vs. 2.27–2.45). With increasing depth for wildland, shelterbelts and native forest, no significant difference in average VESS scores for layers 50–75 cm and 75–100 cm was found.

3.2 | Quantitative characteristics of soil structure

Under wildland steppe vegetation, the 0–25 cm soil layer at site 1 had the highest content of the aggregates of 10–7 mm fraction (20.1%). Rather uniform distribution was observed in 7–5, 5–3, 3–2 and 2–1 mm fractions (10.1–13.8%). AVF content decreased from 87.0% in the 0–25 cm layer to 59.3% in the 75–100 cm layer (Figure 4). Under the plantations of *Robinia pseudoacacia* at site 2, the aggregates of 3–2 mm (17.2%) and 2–1 mm (20.3%) predominated in the 0–25 cm layer. AVF content in the surface layer was 89.3%, while decreasing towards the lower layer to 60.6%. Under *Quercus robur* plantations at site 3, similar patterns of the aggregate fraction distribution were observed: aggregates of 3–2 mm (17.6%) and 2–1 mm (21.0%) fractions predominated in the surface layer, where AVF content was 90.3%. No statistically significant differences were found in the multiple comparison of AVF content between Wildland and Shelterbelts (Table 2). On the other hand, the AVF content in the soils of the studied Native forest sites is statistically significantly higher ($p < .05$) compared with the soils of the Wildland and Shelterbelts. The content of earthworm casts in the surface 10 cm layer was 18.75% under wildland steppe vegetation (site 1), 18.71% under Robinia pseudoacacia (site 2), and 22.17% under Quercus robur (site 3) (Table 2). When comparing earthworm casts content between Wildland and Shelterbelts, no statistically significant differences were found. However, earthworm casts content in Native forest soils is statistically significantly higher ($p < .05$) compared with Wildland and Shelterbelts. SOC content under herbaceous wildland steppe vegetation (site 1) was 3.32% in the 0–10 cm layer and almost twice less in the 10–25 cm layer (1.68%). SOC in the 0–10 cm layer under the shelterbelt Quercus robur plantations (site 3) was 1.94%, and slightly decreased towards the 10–25 cm layer. Soils under Robinia pseudoacacia plantations (site 2) contained the least organic carbon content in both studied layers (Table 2). When comparing SOC content between Shelterbelts and Native forest, statistically significant differences were found: SOC content in Native forest soils is statistically significantly higher ($p < .05$) by 1.7–3.2 (0–10 cm layer) and 1.3–3.8 times (10–25 cm layer), compared with the corresponding layers of Shelterbelts soils.

Soils of ravine forests had high levels of aggregation of the whole soil profile (Figure 4). On the slope of the ravine, AVF content in the 0–25 cm layer was 94.7%; aggregates of 3–2 mm (20.0%) and 2–1 mm (34.2%) fractions dominated. Similar aggregate distributions were observed in the 25–50 and 50–75 cm layers. Even in the 75–100 cm layer, AVF content was 75.0%. In the ravine bottom, aggregates of 5–3 mm (20.3%), 3–2 mm (19.8%) and 2–1 mm (27.3%) fractions predominated in the layer of 0–25 cm. In the 25–50 cm layer, the aggregate distributions were also similar. AVF content was high throughout the entire soil profile, from 96.2% in surface layer to 83.0% in the 75–100 cm layer. Aggregates of 5–3 mm (19.9%), 3–2 mm (29.6%) and 2–1 mm (25.7%) fractions also dominated in the surface layer of floodplain forest soils. The second 25–50 cm layer was characterized by a similar aggregate

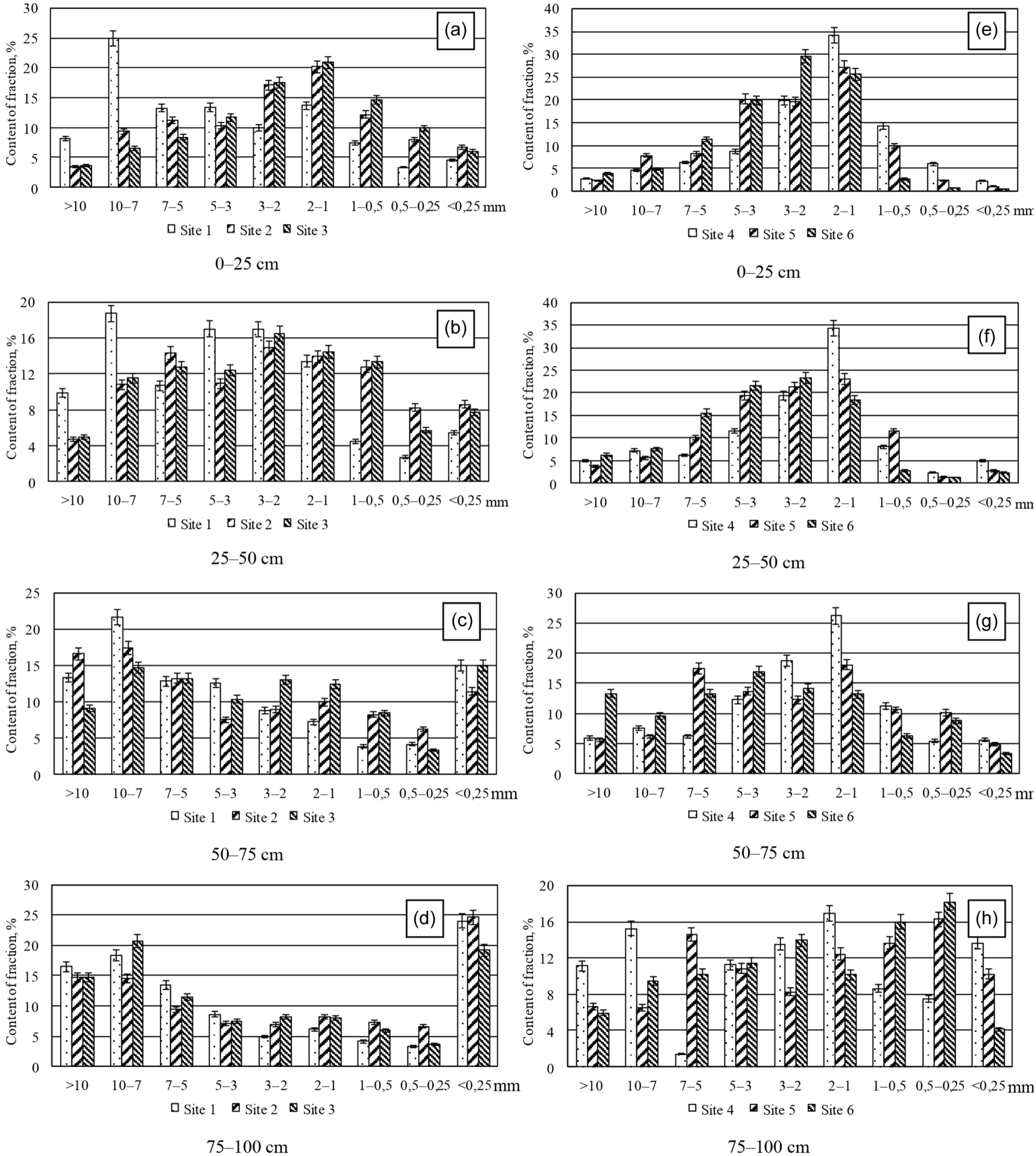

FIGURE 4 Aggregate size distribution of the soils: (a–d) 0–25, 25–50, 50–75, 75–100 cm layers (Site 1, Site 2, Site 3), respectively; (e–h) 0–25, 25–50, 50–75, 75–100 cm layers (Site 4, Site 5, Site 6), respectively. Error bars indicate variation within 5% of parameter.

distribution. AVF content varied across the profile floodplain soil within narrow limits, from 95.3% in the 0–25 cm layer to 89.7% in the 75–100 cm layer. The content of earthworm casts in the surface 10 cm layer was 64.3% under the forest on the ravine slopes, 61.78% in the ravine bottom and 70.16% under the floodplain forest (Table 2).

The highest SOC content was found in floodplain forests (Table 2): 6.12% in the surface 0–10 cm sublayer and 2.86% in the 10–25 cm sublayer. Ravine forest soils contained significantly less SOC in their surface 10 cm sublayer (3.38%–3.52%), while SOC values in the 10–25 cm sublayers were similar in those soils (2.38%–2.84%).

TABLE 2 Content of earthworm casts, agronomically valuable fraction (AVF) and soil organic carbon (SOC) under different vegetation types (x ± SD, $n = 3$).

	Land use system					
	Wildland	Shelterbelts		Native forest		
Layer, cm	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Earthworm casts (%)						
0–10	18.75 ± 1.28^{a}	18.71 ± 1.05^{a}	22.17 ± 1.45^{a}	64.3 ± 2.59^{b}	61.78 ± 1.77^{b}	70.16 ± 2.55^{c}
AVF (%)						
0–25	87.0 ± 1.6^{a}	89.3 ± 1.6^{a}	90.3 ± 1.7^{a}	94.7 ± 0.9^{b}	96.3 ± 1.6^{b}	95.3 ± 2.0^{b}
SOC (%)						
0–10	3.32 ± 0.03^{a}	1.52 ± 0.12^{b}	1.94 ± 0.04^{c}	3.38 ± 0.05^{a}	3.52 ± 0.15^{a}	6.12 ± 0.07^{d}
10–25	1.68 ± 0.07^{a}	0.76 ± 0.05^{b}	1.78 ± 0.04^{a}	2.38 ± 0.05^{c}	2.84 ± 0.12^{d}	2.86 ± 0.06^{d}

Note: The different letters indicate statistically significant differences in the means of the compared pair according to the Tukey criterion ($p < 0.05$).

3.3 | Relating visual evaluation to quantitative characteristics of soil structure

VESS scores had a significant ($p < .05$) negative correlation with the earthworm bioturbation, AVF and SOC (Figure 6). The highest correlation was found between VESS score and earthworm casts content ($r = -.98$). Likewise, VESS strongly correlated with SOC content ($r = -.78$) and AVF content ($r = -.87$). The calculated correlations indicate that the values of the quantitative characteristics quite closely coincide with the VESS scores: a 'good' visual assessment of the structure (low VESS score) corresponds to a high content of earthworm casts, AVF and SOC, and, conversely, with an increase in VESS scores, a decrease in the content of earthworm casts, AVF is noted and SOC. This confirms the effectiveness and sensitivity of visual evaluation of soil structure in the studied conditions.

4 | DISCUSSION

The studies of low-intensity land use systems of the steppe zone of Ukraine conducted by us during 2016–2021 are a continuation of long-term monitoring observations (Belova & Albiczkaya, 1989; Belova & Travleev, 1999; Gritsan, 2000) quality of black soils of one of the large agricultural regions of the world. We found out that steppe black soils structural quality in low-intensity land use systems is determined by type of vegetation. According to the VESS scores, quantitative characteristics of the structure and the intensity of bioturbation of earthworms, the highest quality of the structure was found in the Chernozems and Phaeozems of natural forests. According to the studies of whole soil profile, it was found that structural quality of the lower part of the soil profile (50–75 cm and 75–100 cm layers) is primarily because of the characteristics of the parent rock. On the contrary, the structural quality of the 0–25 cm and 25–50 cm layers is determined by the type of plant vegetation and the corresponding ecological conditions that are formed under plant influence (Belova & Travleev, 1999; Gritsan, 2000; Rolo et al., 2023). When comparing the VESS (Sq) scores of the studied sites (Table 1), it can be noted that their average values for the Sites 4–6 (native forest) do not statistically differ from each other, but they are lower than the average scores for the Sites 1–3 (wildland and shelterbelts). This trend was also obvious when comparing SubVESS (Ssq) scores of the study sites for the deeper 25–50 cm layer. The average SubVESS (Ssq) scores for all studied sites for both the 50–75 cm layer and the 75–100 cm layer formed statistically homogeneous groups, demonstrating no significant differences inside them. The main feature of the natural forest soils, as compared to soils under herbaceous and shelterbelt woody vegetation, was a much higher bioturbation earthworm activity in the 0–25 cm layer. Moreover, higher bioturbation activity in forest soils extends to deeper genetic horizons and is clearly noticeable in the 25–50 cm layer. The type of forest vegetation largely impacts the species composition and abundance of soil macrofauna (Kooch et al., 2018; Kunakh et al., 2023; Visscher et al., 2023; Zhukov et al., 2019); this makes the bioturbation activity of earthworms one of the key factors of soil structural quality (Guimarães et al., 2011; Piron et al., 2017; Yakovenko & Zhukov, 2021). Accordingly, forest soils had higher structural quality in terms of visual structure evaluation in the layers of 0–25 cm (Sq score was 1.31–1.34) and 25–50 cm (Ssq score was <2). Similar results of VESS assessments were reported for soils in other geographical areas of the world (Aji et al., 2021; Auler et al., 2017; Cherubin et al., 2018; Guimarães et al., 2013; Mutuku et al., 2021). The first contrast sublayer within 0–25 cm (which corresponds to the genetic horizon A1) had a greater thickness in soils of natural forests (Figure 3). VESS of this layer is formally equal to Sq = 1 (highest) in soils of all types of land use: under steppe vegetation, shelterbelt plantations and natural forests. However, considering the well-known positive impact of earthworm casts on soil structural quality (Hallam & Hodson, 2020; Le Bayon et al., 2021; Van Groenigen et al., 2019; Wang et al., 2021), the actual structural quality of natural forest soils is higher. Our findings provide reasons for giving higher weight to earthworm bioturbation as a key indicator of structural quality during VESS assessments. Similar considerations were made by the authors studying tropical soils in Brazil (Cherubin et al., 2018; Valani et al., 2020).

Quantitative indicators of soil structure varied in agreement with the visual assessment scores. The average agronomical valuable fraction (AVF) values for the surface 0–25 cm layer for the Sites 1–3 (wildland and shelterbelts) were similar, but their values were lower than those for Sites 4–6 (native forest). Natural forest soils had the highest values of AVF content in every layer of soil profile (Figure 4). The content of AVF naturally decreases downside the profile in all studied soils. In natural forest soils, this decrease was gradual, while soils under shelterbelt plantations and steppe vegetation demonstrated a sharper decrease in AVF content towards the lower profile horizons. When comparing the content of earthworm casts (coprolites) among the studied sites (for the surface 0–10 cm layer), it should be noted that their average content for the Sites 1–3 (wildland and shelterbelts) was similar; with that, it was 2.8–3.7 times lower than the average content of coprolites at Sites 4–6 (native forest) (Table 2). In forest soils, all investigated aggregate fractions contained more than 60% of earthworm casts (Table 2 and Figure 5). For the soil organic carbon (SOC) in the 0–10 cm soil layer, it can be noted that Site 1 (wildland) as well as Sites 4–6 (native forest) had statistically higher values than Sites 2 and 3 (man-made shelterbelts). The 10–25 cm layer was less rich in organic matters than the 0–10 cm layer; however, it contained higher average SOC values in the Sites 4–6 (native forest) compared with Sites 1–3 (wildland and shelterbelts).

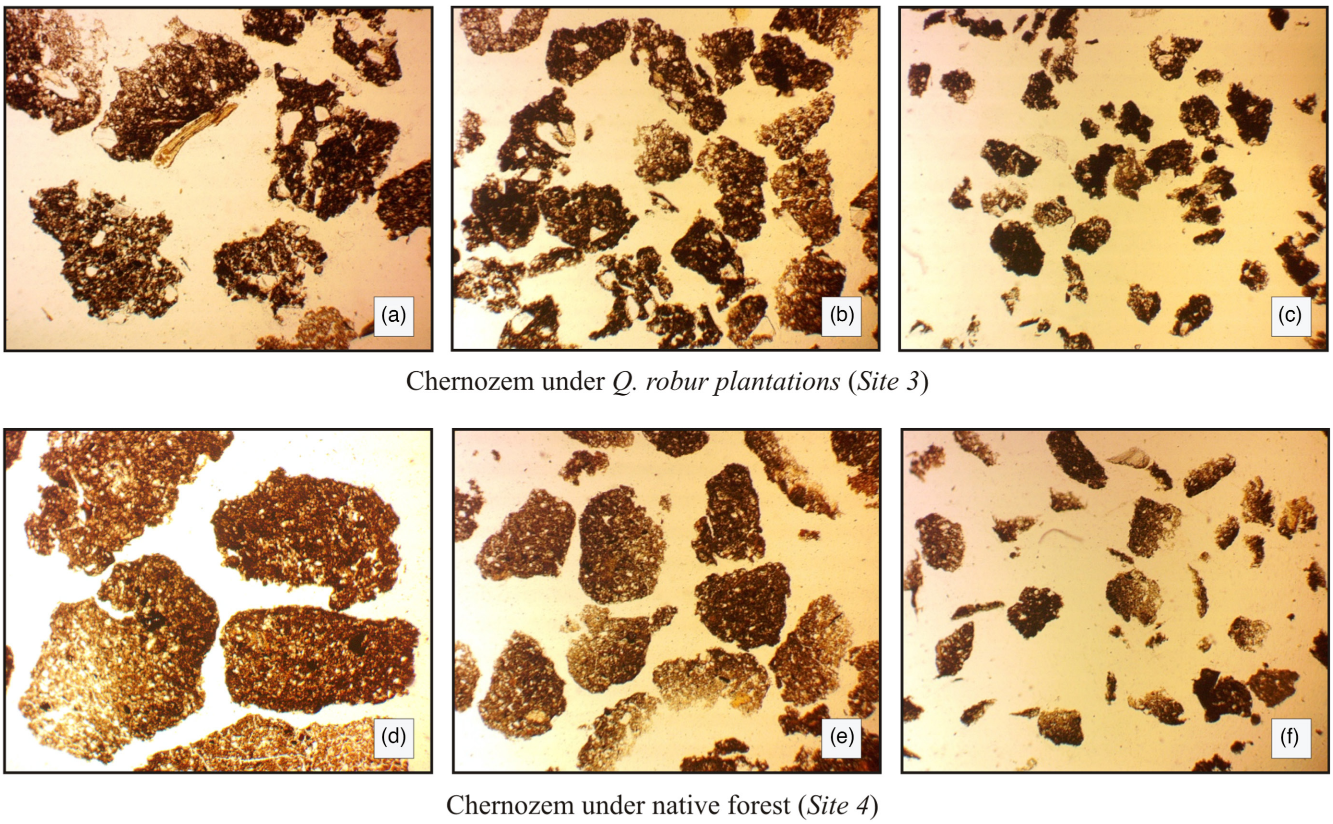

FIGURE 5 Photomicrographs of aggregates illustrate the higher intensity of earthworm bioturbation of the surface 0–10 cm layer of Chernozems in natural forest (Site 4) compared with *Quercus robur* plantations (Site 3). Site 3, aggregate fractions: (a) 2–1 mm, (b) 1–0.5 mm, (c) 0.5–0.25 mm. Site 4, aggregate fractions: (d) 2–1 mm, (e) 1–0.5 mm, (f) 0.5–0.25 mm. Width of the photographs: 3.48 mm, PPL. Earthworm casts, as compared with aggregates of other genesis, had granular isometric and slightly elongated shape, smooth or slightly wavy surface, homogeneous distribution of organogenic components in the mineral groundmass.

The effect of different plant vegetation types on soil quality revealed by this study is in good agreement with the studies of the positive impact of forest vegetation upon aggregate size distribution (An et al., 2010; Gorban, 2021; Paramanik et al., 2020; Wu et al., 2022) and organic carbon content of various soils (Gorban et al., 2020; Nadal-Romero et al., 2016; van Hall et al., 2017; Wiśniewski & Märker, 2019; Xiang et al., 2021).

It was established that VESS scores significantly correlate with quantitative characteristics of steppe black soil structure. Significant earthworm casts content, AVF and high SOC were associated with lower VESS scores, that is higher structural quality (Figure 6). The highest degree of correlation of visual assessments was found with earthworm casts content. Similar statistically significant correlations of VESS scores with other physical properties of soil quality were also found, for example, for soil porosity, bulk density, air capacity, saturated hydraulic conductivity, penetration resistance and structure (Cherubin et al., 2017; Cornelis et al., 2019; Guimarães et al., 2013; Lin et al., 2022; Moncada et al., 2014; Olivares et al., 2023). High correlation between VESS scores and quantitative soil structure characteristics found in this study indicates the effectiveness of visual assessment methods for field determination of steppe soil quality. Chernozems and Phaeozems form the soil cover of the leading agricultural regions of the world (FAO, 2015, 2022a). Such 'black soils' have a similar nature of use, related problems, and ways to solve them (FAO, 2022b), in particular, the introduction of agroforestry systems. Therefore, the results of our research can be attractive in a scientific and practical aspects, and the implemented methodical approach can be tested in a wider geographical dimension.

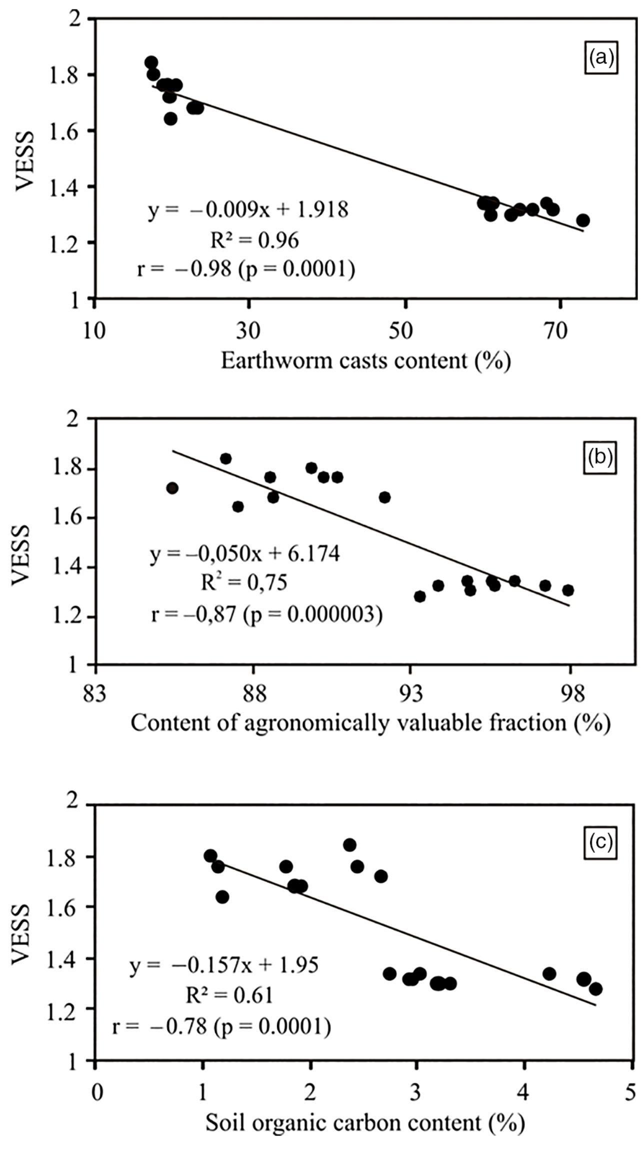

FIGURE 6 Relationships between visual evaluation of soil structural quality (VESS Sq score) and quantitative characteristics of soil structure in steppe wildland, shelterbelt plantations and native forest land use systems: (a) earthworm casts in 0–10 cm layer, (b) agronomically valuable fraction in 0–25 cm layer, (c) soil organic carbon in 0–25 cm layer.

5 | CONCLUSIONS

We demonstrated that in conditions of the steppe zone of Ukraine the quality of black soils structure in low-intensity land use systems (wildlands, shelterbelts and natural forests) is determined by the type of vegetation. Native forest vegetation defines the highest soil structural quality, according to a range of both visual and quantitative characteristics, including VESS, earthworm bioturbation, SOC and AVF content. High correlation of soil structure visual evaluation scores with content of earthworm casts, agronomically valuable fraction and soil organic carbon was revealed.

Thus, VESS evaluation of structural soil quality in the Ukrainian steppe zone confirmed that natural forests and shelterbelts are effective, long-lasting, economically justified and environmentally sustainable elements of agroforestry systems, positively impacting the quality of black soils structure in steppe landscapes. Our data suggest further ways to improve resolution of VESS techniques to distinguish similar soils of low-intensive land use, for example by assigning higher weight to earthworm bioturbation parameters, which are the significant indicators of soil structural quality. VESS/SubVESS methods proved their efficacy and usefulness in the study of soils of steppe landscapes, they could be recommended for wider use in soil assessment in different natural zones of Ukraine.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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