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Original Paper

Organic Carbon Sequestration Across Soil Aggregates of Morphologically Different Soils

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Soil organic matter (SOM) and its incorporation into soil aggregates play a crucial role in carbon sequestration, which is essential for sustainable agriculture and climate change mitigation. This study focuses on the influence of different soil types on soil structure and the capacity of soil aggregates to retain carbon. The objectives were: (1) to compare soil structure across different soil types, (2) to quantify the content of SOM in size-fractions of aggregates, and (3) to identify relationships between SOM and individual size-fractions of aggregates. The research was conducted in a field at Dražovce near Nitra city (western Slovakia). Samples from the Ap and A horizons of four soil profiles were analyzed for aggregate size-distribution, carbon contents, and the carbon sequestration index (KSC). The results indicated that Cambisol exhibited the highest aggregate stability, while Chernozems showed the highest SOM content but the lowest KSC. Calcisol demonstrated the greatest sequestration potential. Aggregate stability was positively correlated with the content of labile carbon, particularly in medium-sized macroaggregates (1–5 mm). These findings highlight the complex interactions between aggregate size, structural stability, and their capacity to sequester carbon.

Keywords: Calcisol, Cambisol, Chernozem, soil organic matter, soil structure

1 Introduction

The fundamental units of soil structure "soil aggregates" and their size distribution are closely linked to the content and quality of SOM (Fulajtár, 2006; Šimanský et al., 2023). In recent years, research has increasingly focused on understanding the mechanisms that influence the formation and stability of aggregates across different soil types, particularly in the context of climate change and sustainable soil management (Basile-Doelsch et al., 2020). SOM serves not only as a nutrient source but also as a major reservoir of carbon, which can be sequestered within soil aggregates. The carbon sequestration process is governed by interactions among plants, microorganisms, and soil mineral particles. The stability of carbon in soil depends on its association with fine-textured fractions (clay) and minerals, as well on the stability of aggregates of different sizes (Six et al., 2004).

Numerous studies have demonstrated that aggregate size-fractions differ in their capacity to bind and stabilize carbon. Macroaggregates generally contain more carbon, albeit in a less stable form, whereas microaggregates are capable of long-term carbon stabilization (Zhang et al., 2025). Differences among soil types such as: Chernozems, Cambisols, and Calcisols are evident not only in their morphological, chemical and mineralogical composition but also in their ability to accumulate and stabilize carbon. These differences may be significant even under identical soil management practices, highlighting the importance of pedogenetic factors in soil structure formation (Gentsch et al., 2024; Kruczkowska et al., 2025). Therefore, it is essential to investigate soil structure and carbon sequestration potential in the context of specific soil types and soil-forming processes. From the perspective of sustainable agriculture and climate change mitigation, identifying soil properties that promote long-term carbon storage is crucial. A key aspect is not only the quantity of SOM but also its distribution across aggregate size-fractions and the stability of these

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fractions (Basile-Doelsch et al., 2020). In this context, it is necessary to quantify organic carbon content in individual size-fractions of aggregates and analyze their relationship to soil structure across different soil types. The objectives of this study were:

1. to determine the extent to which different soil types influence soil structure under uniform soil management,
2. to quantify the content of SOM and the carbon sequestration potential in individual size-fractions of aggregates,
3. to identify relationships between SOM including the carbon sequestration index and soil aggregates.

These objectives address current challenges in soil science and contribute to a deeper understanding of the mechanisms that affect soil structural stability and the soil's capacity to sequester carbon.

2 Material and Methods

2.1 *Study Site and Climate*

The research field is located on the western outskirts of the city of Nitra, within the territory of the village of Dražovce. The village lies in a transitional zone between the western foothills of the Tribeč Mountains characterized by granitoid formations and Triassic dolomites belonging to the Carpathian geological system, and the Nitra River valley, which is part of the expansive Great Danubian Lowland. The terrain of the Tribeč slopes and the elevated sections of the Nitra valley is predominantly covered by colluvial sediments originating from weathered Carpathian rocks. Additionally, the area is blanketed by a widespread layer of Quaternary loess, composed of silty-loamy material deposited under periglacial conditions during the last glacial period (Hreško et al., 2006).The dominant soil types identified in the vicinity of the research site include Eutric Dolomitic Leptosol, Luvic Chernic Phaeozem, Nudiargic Luvisol, Eutric Cambisol, Haplic Calcisol, Vermic Chernozem, and Ekranic Technosol (Jankowski et al., 2018). The area is classified as a very warm to warm climatic region. Average annual air temperatures range from 7.5 to 10 °C. July is the warmest month (16 to 20.5 °C), while January is the coldest (-1 to -4 °C). Maximum air temperatures recorded at the Nitra meteorological station exceed 35 °C (absolute maximum 38.9 °C), whereas minimum temperatures fall below -25 °C (absolute minimum -27.7 °C) (Hreško et al., 2006).

2.2 *Soil Management Practice in the Field, Description of Soil Profiles, and Soil Sampling*

A field survey combined with soil sampling was conducted in autumn 2024. Following a reconnaissance of the selected site, four soil pits were located and excavated along a transect extending from northeast to southwest. The distance between the first and fourth pits was approximately 130–135 m (Figure 1). At the time of soil survey, the site had been disked to a depth of 10–12 cm and was largely devoid of vegetation (minimal weed cover). In the current year, winter wheat was cultivated on the field.

The selected plot has been continuously used for several decades for the cultivation of common market crops, primarily cereals (wheat, barley, maize) and oilseeds (sunflower, rapeseed), managed under conventional

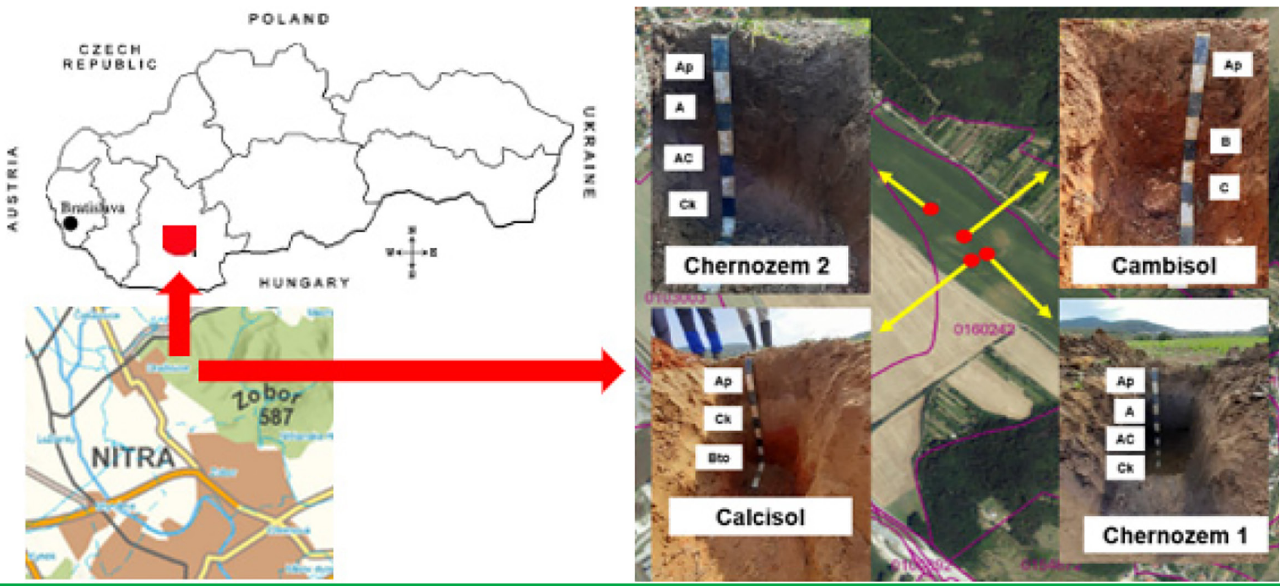

Figure 1 Study site location and studied soil profiles

agronomic practices. Autumn ploughing to a depth of 20–25 cm is typically performed for most crops. Subsequent seedbed preparation depends on the specific crops. During the growing season, chemical plant protection is applied as needed, based on pest, disease, or weed thresholds. In recent years, fertilization has primarily involved the incorporation of post-harvest and root residues, along with the application of nitrogen fertilizers. Nitrogen application rates vary between 30 and 150 kg/ha, depending on the crops. After delineating and excavating the soil pits, morphological descriptions of the soil profiles were conducted, and soil types were classified according to the World Reference Base for Soil Resources (WRB, 2015). Detailed descriptions of the soil profiles, along with their classification, are provided herein:

Chernozem 1: Vermic Chernozem (Aric, Colluvic, Loamic, Pachic)

- Ap-horizon: 0–25 cm, humus plough horizon, 7.5 YR 3/3 (wet), silty loam, moderate granular structure, calcium carbonate <1%
- A-horizon: 25–85 cm, 7.5 YR 2/1 (wet), silt loam, moderate granular structure, calcium carbonate to 1%
- AC-horizon: 85–95 cm, 7.5 YR 5/6 (wet), silt loam, calcium carbonate <1%
- Ck-horizon: >95 cm, 7.5 YR 6/6, silt (wet), calcium carbonate >5%

Calcisol: Haplic Calcisol (Aric, Endochromic, Hypocalcic, Loamic, Ruptic)

- Ap-horizon: 0–25 cm, 10 YR 4/4 (wet), silt loam, strong lumpy structure, calcium carbonate >5%
- Ck-horizon: 25–52 cm, 10 YR 6/4 (wet), silt loam, moderate granular structure, calcium carbonate >5%
- Bto-horizn: >60 cm, 5YR 4.5/7 (wet), buried argic horizon with residual accumulation of sesquioxides, clay loam, massive structure, partially hardened

Cambisol: Eutric Cambisol (Aric, Endochromic)

- Ap-horizon: 0–25 cm, 2.5 YR 5/4 (wet), clay loam, moderate granular structure
- B-horizon: 10 R 4/8 (wet), clay, blocky subangular structure
- BC-horizon: 10 R 5/7 (wet), clay, massive structure, partially hardened

Chernozem 2: Vermic Chernozem (Aric, Loamic)

- Ap-horizon: 0–25 cm, humus plough horizon, 10 YR 2/3 (wet), loam, moderate granular structure, calcium carbonate to 1%
- A-horizon: 25–35 cm, 10 YR 2/3 (wet), silt loam, moderate granular structure, calcium carbonate >5%
- AC-horizon: 35–55 cm, 10 YR 5/6 (wet), silt loam, calcium carbonate >5%
- Ck-horizon: >95 cm, 10 YR 6/6 (wet), silt, calcium carbonate >5%

For the purposes of this study, soil samples were collected from the Ap horizons of all identified soil types. In the case of Chernozems, additional samples were also taken from the A horizons, as these exceeded 25 cm in thickness. Samples were collected in a disturbed state, with care taken to preserve the integrity of soil aggregates. The samples were subsequently transported to the laboratory and air-dried at room temperature.

2.3 Soil Analysis

Standard methods summarized in the publication by Hrivňáková et al. (2011) were used to determine the individual size-fractions of soil aggregates obtained by dry sieving (DSA) and wet sieving (WSA). Soil aggregates smaller than 0.25 mm were classified as microaggregates (mi), while those larger than 0.25 mm were considered macroaggregates (ma). The size-fractions of DSA and WSA greater than 5 mm, between 1–5 mm, and between 0.25–1 mm were designated as large, medium, and small, respectively. Based on these aggregate size-distribution, the structural coefficient (KSd), the water stability coefficient (KSw), and the percentage of macroaggregate destruction (PAD) were calculated (Šimanský et al., 2023).

Within each aggregate size-fraction, the contents of organic carbon (C_{org}) and labile carbon (C_L) were determined. Using these values, the potential carbon sequestration index (*KSC*) was calculated for each WSA size-fraction according to Equation (1).

$$KSC = \frac{C_{org} - C_L}{C_L} \quad (1)$$

where: C_{org} – content of organic carbon in size-fractions of water-stable aggregates; C_L – content of labile carbon in size-fractions of water-stable aggregates

2.4 Statistical Analysis

All statistical evaluations were performed using the software Statgraphics Centurion XV.I (Statpoint Technologies, Inc., Warrenton, VA). The results are presented as means accompanied by standard deviations. To assess differences between the Ap and A horizons across all soil types, a one-way analysis of variance (ANOVA) was applied, followed by Tukey's post hoc test at a significance threshold of $p < 0.05$. Relationships between the size-fractions of DSA and WSA and the SOM content were examined using a correlation matrix. These associations were quantified using Pearson's correlation coefficients, evaluated at various probability levels, with statistical significance set at $p < 0.05$.

3 Results and discussion

3.1 Soil Structure

The current structural state, evaluated using the structural coefficient (KSd), was relatively uniform across all A horizons of the soils assessed along the transect (Table 1). Similarly, the total content of DSAmaand DSAmi was relatively consistent in the A horizons of the studied soils (Figure 2A–D). However, when DSAma were further divided into large (>5 mm), medium (1–5 mm), and small (0.25–1 mm) size-fractions, differences in their contents were observed among the A horizons. Variations were also noted within the A horizons of Chernozems, which had mollic A horizons exceeding 25 cm in thickness; therefore, Ap horizons were separately distinguished within the A horizons.

Table 1 Soil structure parameters for A horizons of studied soils

Soil type	KSd	KSw	PAD
Cambisol	1.12a	2.15a	0.16a
Chernozem 1	1.62a	2.78ab	0.25a
Chernozem 2	1.65a	4.35bc	0.25a
Calcisol	2.02a	4.96c	0.25a
$HSD_{0.05}$	0.4352	0.0006	0.2977

KSd – structural coefficient, KSw – water stability coefficient, PAD – % macroaggregate destruction, $HSD_{0.05}$ – Honest Significant Difference at the 0.05 significance level (Tukey's post hoc test); different letters (a, b, c) between lines represent statistical differences at $p < 0.05$ according to the Tukey test

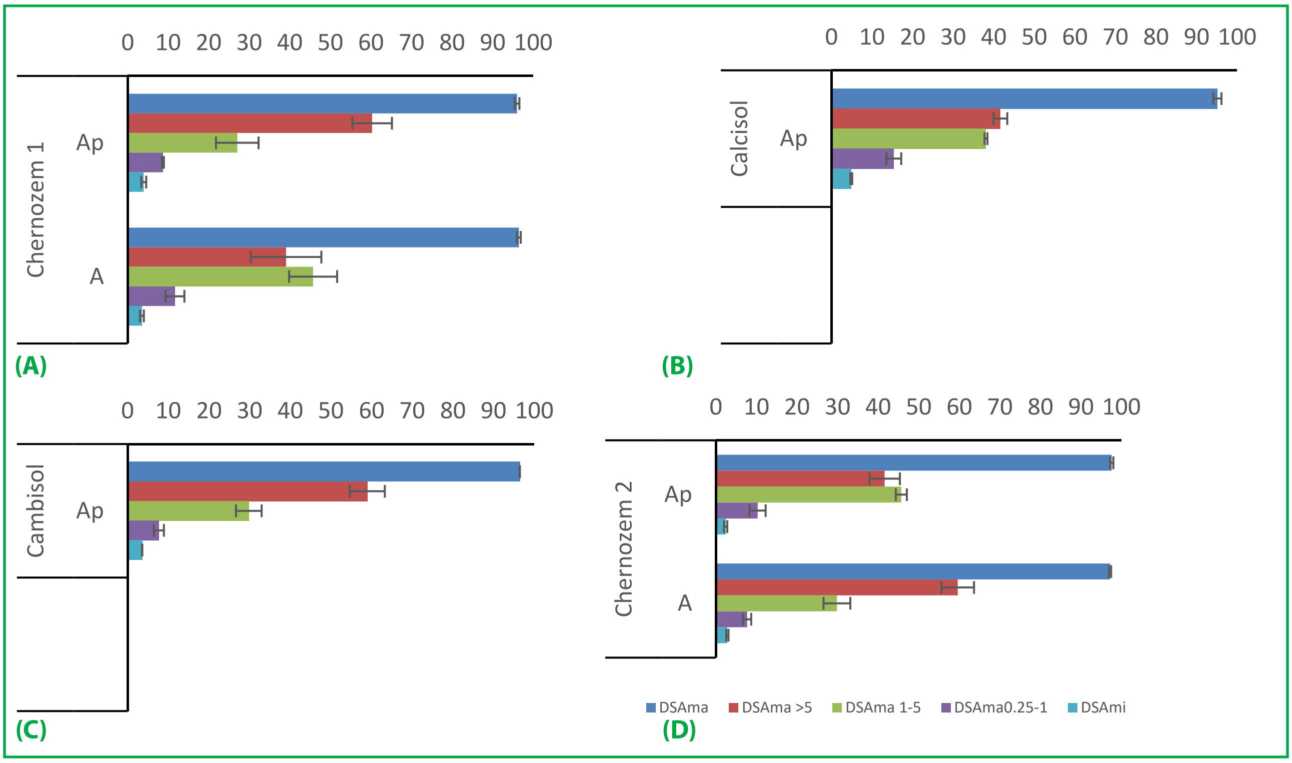

Figure 2 Average contents (means) of dry-sieved aggregates (DSA)
DSAma – macroaggregates included size-fractions >5, 1–5, and 0.25–1 mm; DSAmi – microaggregates <0.25 mm. Panels A–D represent different soil types
Error bars represent ± standard deviation

The highest content of DSAma >5 mm in Ap horizons was recorded in the following order: Chernozem 1 > Cambisol > Calcisol > Chernozem 2. When comparing A horizons across soil types, the order of DSAma >5 mm content from highest to lowest was: Cambisol > Chernozem 2 > Chernozem 1 > Calcisol. The highest content of medium DSAma (1–5 mm) was found in the Ap horizon of Chernozem 2, followed by Calcisol, Cambisol, and the lowest in Chernozem 1. The greatest proportion of small DSAma (0.25–1 mm) was observed in the Ap horizon of Calcisol, followed by Chernozem 2, Chernozem 1, and Cambisol. These differences can be attributed to variations in mineralogical composition, soil texture, and organic matter content among the soil types (Fulajtár, 2006; Polláková et al., 2018).

The water stability of soil structure in the A horizons of the different soil types within the study area was also evaluated. The water stability coefficient (KSw) was significantly influenced by soil type (P = 0.0006). Cambisol exhibited significantly higher KSw values compared to Calcisol and Chernozem 1. No statistically significant differences were found between the A horizons of the two Chernozems (Table 1). The percentage of macroaggregate destruction (PAD) did not vary significantly across the A horizons of all soil types along the transect. In fact, Chernozems and Calcisol had similar average PAD values.

Overall, the A horizons of the studied soils exhibited WSAma contents ranging from 81% to 89%, in the following order from highest to lowest: Cambisol >Chernozem 2 >Calcisol >Chernozem 1. Conversely, WSAmi contents followed the opposite trend (Figure 3A–D). Substantial differences were observed between the A and Ap horizons of both Chernozems, as well as among all Ap horizons of the studied soil types, particularly in the content of large WSAma (>5 mm). Chernozem 1 showed a marked difference in WSAma >5 mm content between its Ap and A horizons, whereas Chernozem 2 exhibited consistent values. Overall, large WSAma (>5 mm) were most abundant in Chernozem 2 and least in Chernozem 1. All soils had comparable contents of medium WSAma (1–5 mm), indicating a satisfactory level of water stability in soil aggregates. However, significant differences in the content of small WSAma (0.25–1 mm) were observed between Chernozem 1 and Chernozem 2.

The variation in WSA size-fractions in the A horizons of the studied soils is directly related to their formation (Fulajtár, 2006; Bryk, 2016; Šimanský et al., 2023). Within a relatively small area, the interplay of diverse soil-

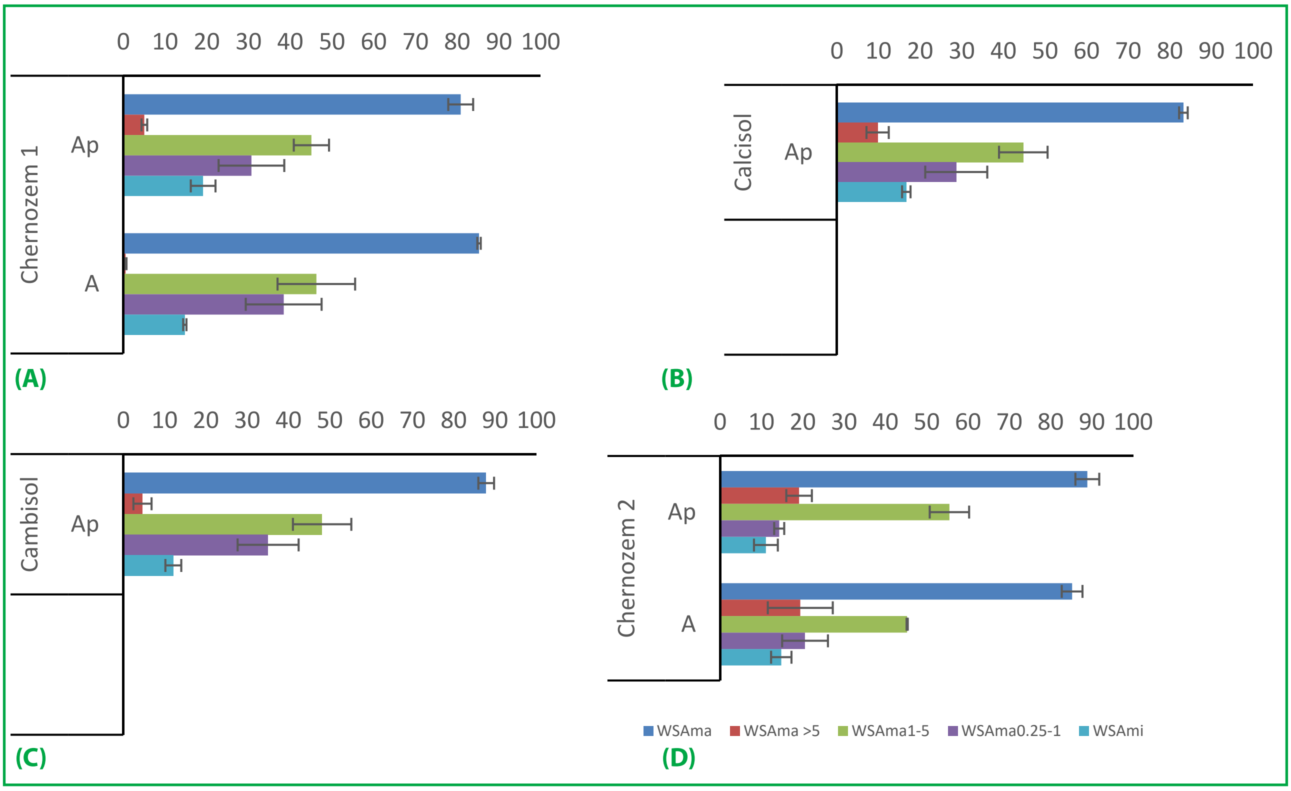

Figure 3 Average contents (means) of wet-sieved aggregates (WSA)
WSAma – macroaggregates included size-fractions >5, 1–5, and 0.25–1 mm; WSAmi – microaggregates <0.25 mm. Panels A–D represent different soil types
Error bars represent ± standard deviation

forming factors and conditions led to the formation of different soil types, each with distinct morphological characteristics, textural composition, and organic matter content. Factors of soil-formation are closely linked to soil structure (Halder et al., 2024; Kruczkowska et al., 2025). Soil structure is also significantly influenced by external factors, including soil management practices such as tillage and fertilization (Gentsch et al., 2024; Halder et al., 2024; Šimanský et al., 2023). However, in this study, such influences were minimized, as the transect was located within a single field subjected to consistent soil management and crop rotation for several decades.

Nevertheless, due to their inherent pedogenic properties such as differences in chemical composition, texture, and SOM, individual soils respond differently to management practices. For instance, Chernozems are generally considered to be highly fertile soils with well-developed and stable structure (Zaujec & Šimanský, 2008). However, the results of this study suggest that Chernozems exhibit considerable variability in their individual size-distribution of aggregates (Figures 2 and 3).

3.2 Potential of Carbon to Accumulate in WSA

In all A horizons of the studied soils, the content of organic carbon (C_{org}) was higher in water-stable macroaggregates (WSAma) than in water-stable microaggregates (WSAmi). A clear trend was observed across all soil types: the larger the WSAma size-fraction, the higher the C_{org} content (Figure 4A–D). In general, macroaggregates tend to contain more carbon than microaggregates (Šimanský & Juriga, 2024; Kruczkowska et al., 2025), which is attributed to the presence of plant roots, fungal hyphae, and their by-products within macroaggregate (Tisdall & Oades, 1980).

The A horizons of both Chernozems exhibited higher contents of all WSAma and WSAmi size-fractions compared to other soil types in the study area. In the A horizon of Chernozem 1, the C_{org} content in large, medium, and small WSAma, as well as in WSAmi, was higher by 5, 29, 27, and 27%, respectively, compared to its Ap horizon. Conversely, in Chernozem 2, the C_{org} content in the same fractions was lower by 29, 25, 4, and 5%, respectively, compared to its Ap horizon (Figure 4D).

The content of labile carbon (C_L) in WSA fractions followed the same trend as C_{org} (Figure 5A–D). The calculated potential carbon sequestration indices (KSC) varied depending on the WSA size-fractions and the specific A horizon of each soil type (Figure 6A–D). For instance, in Chernozem 1, the Ap horizon showed higher KSC values

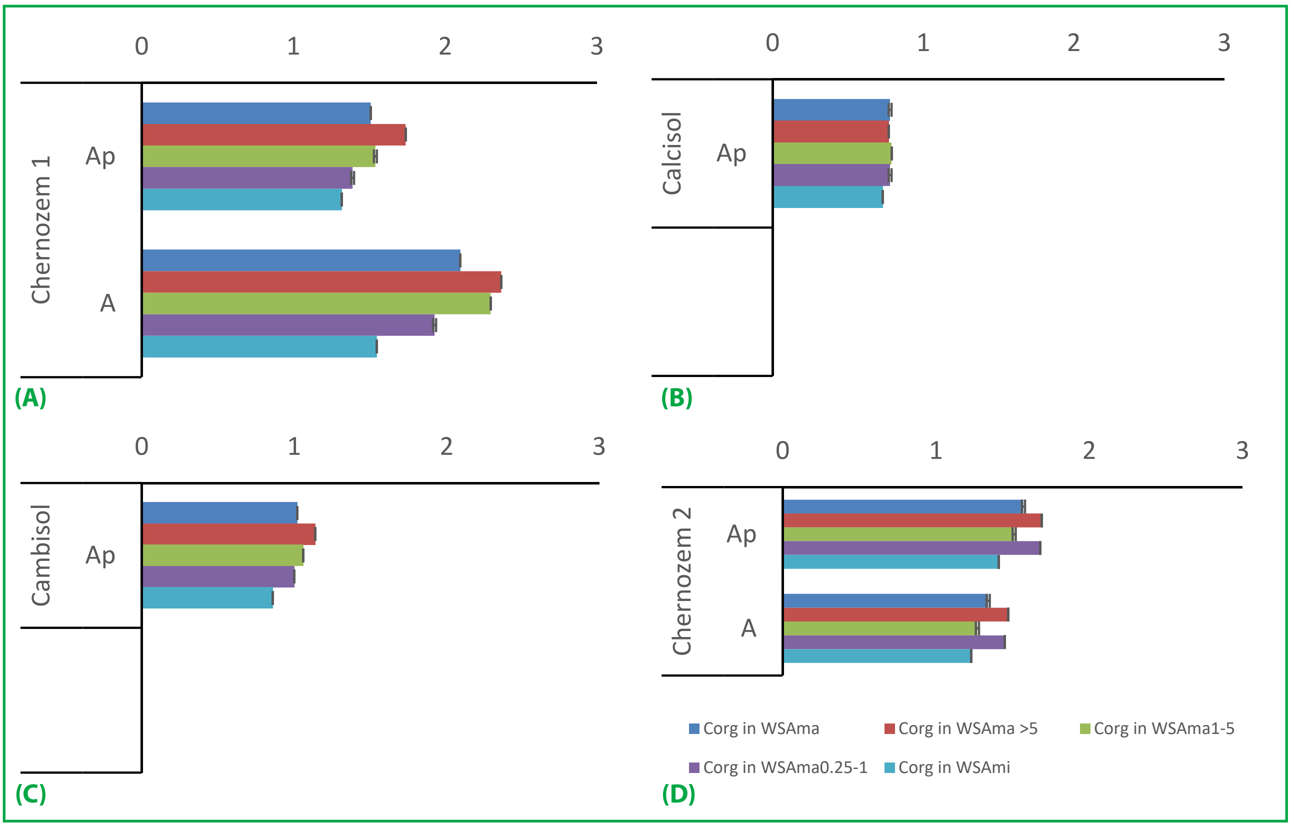

Figure 4 Average contents (means) of organic carbon (C_{org}) in size-fractions of water-stable aggregates (WSA)
For explanations of the abbreviations WSAma and WSAmi, see Figure 3. Panels A–D represent different soil types
Error bars represent ± standard deviation

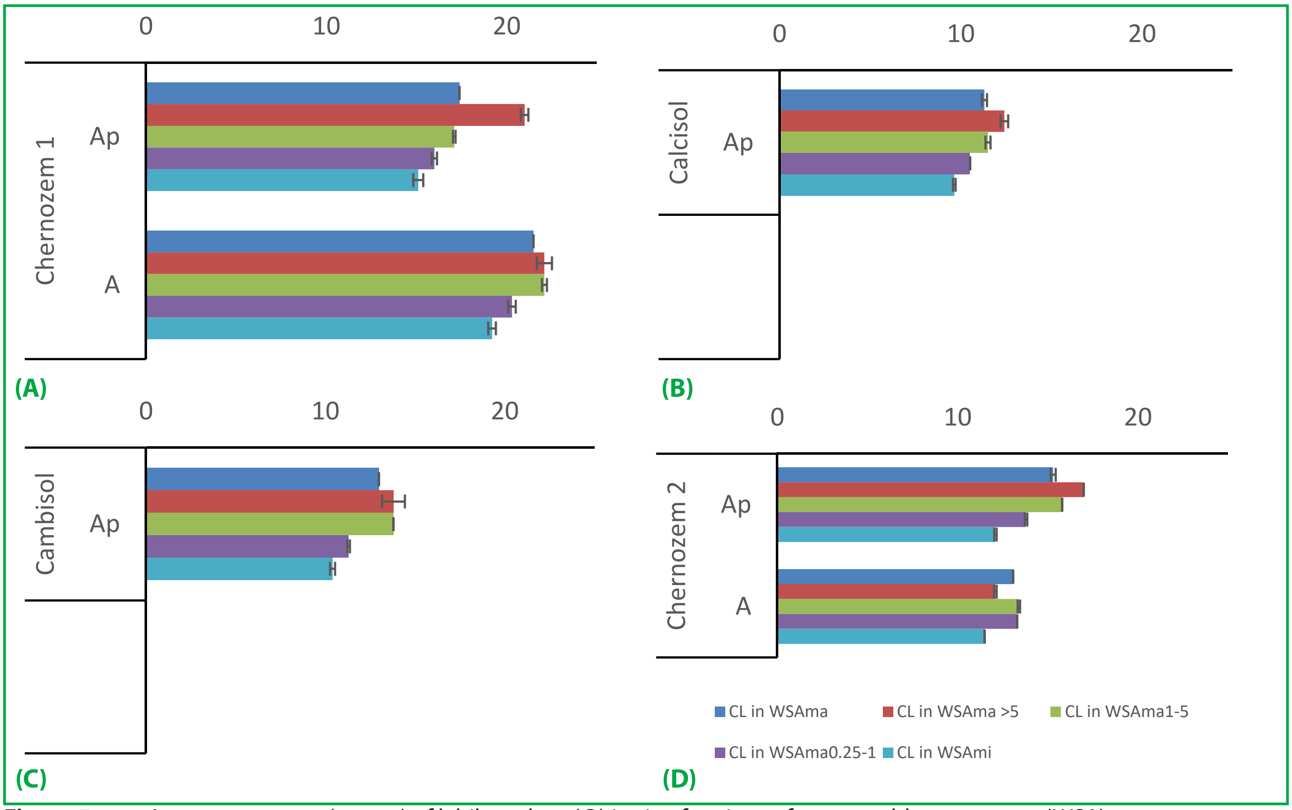

Figure 5 Average contents (means) of labile carbon (C_L) in size-fractions of water-stable aggregates (WSA)
For explanations of the abbreviations WSAma and WSAmi, see Figure 3. Panels A–D represent different soil types
Error bars represent ± standard deviation

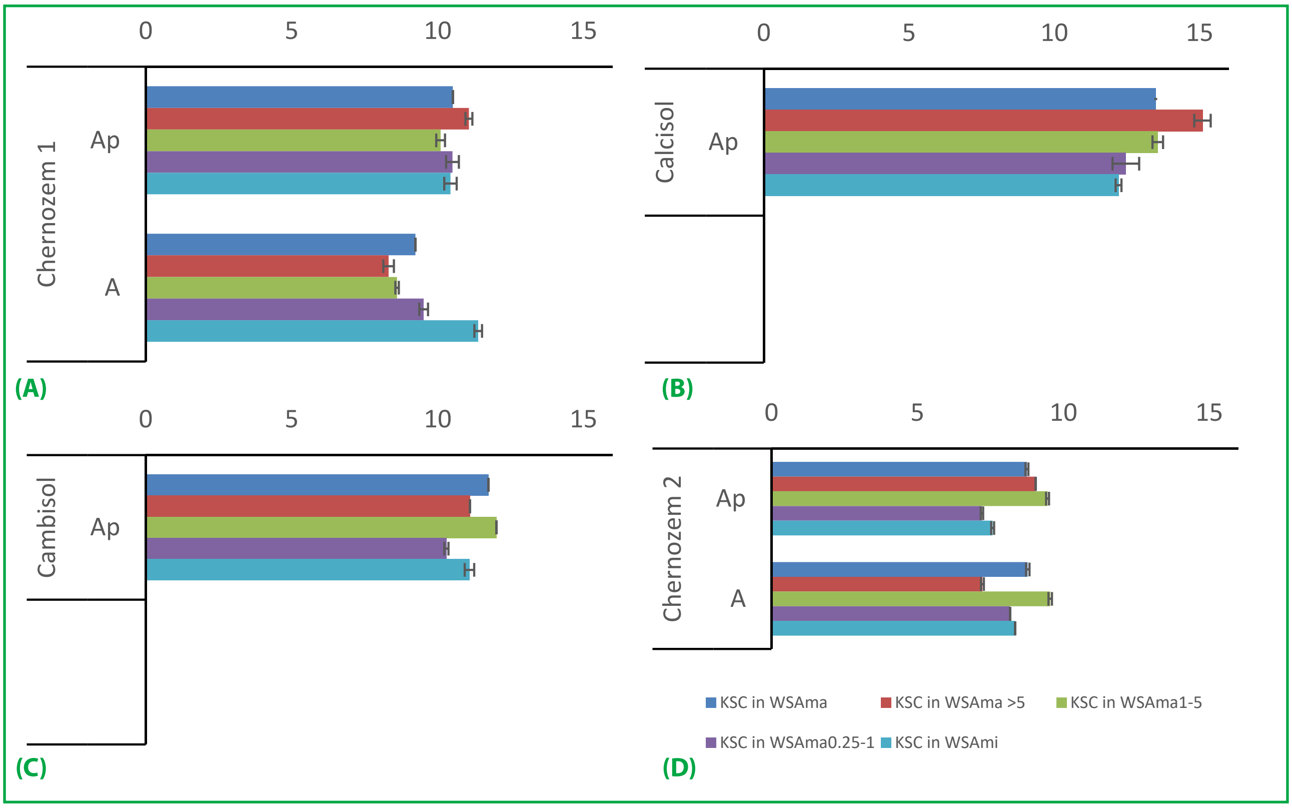

Figure 5 Average contents (means) of labile carbon (C_L) in size-fractions of water-stable aggregates (WSA)
For explanations of the abbreviations WSAma and WSAmi, see Figure 3. Panels A–D represent different soil types
Error bars represent ± standard deviation

in WSAma compared to the A horizon, whereas in the A horizon, KSC values in WSAmi were 9% higher than in the Ap horizon. In Chernozem 2, opposite trends were observed. Overall, the highest KSC values were found in large WSAma size-fractions (>5 mm), and in general, both WSAma and WSAmi in Calcisol and Cambisol exhibited the greatest sequestration potential. In other words, soils with higher fertility tend to have higher C_{org} or C_L contents in WSA size- fractions, but paradoxically, lower carbon sequestration indices. This suggests that the content of organic carbon alone is not sufficient indicator of sequestration potential, carbon stability and its distribution across aggregate size-fractions are equally critical.

3.3 Correlations Between Aggregates and SOM within Aggregates

The content of DSAma increased with rising levels of C_L in WSAmi, whereas the content of DSAmi increased as C_L in WSAmi decreased. The carbon sequestration index (KSC) in WSAma particularly in large and medium size-fractions as well as in WSAmi, decreased with increasing DSAma content. In contrast, the opposite trend was observed for DSAmi (Table 2). Higher values of PAD were directly associated with elevated C_L levels in WSAma, especially in the medium sized-fractions (1–5 mm). The stability of WSA aggregates (KSw) was primarily influenced by higher C_L content in medium WSAma (1–5 mm), as well as by C_{org} in large WSAma (>5 mm), medium WSAma (1–5 mm), and WSAmi. Greater aggregate stability corresponded with higher KSC values in WSAmi.

Overall, higher C_{org} content in large and medium WSAma and WSAmi was associated with lower contents of large WSAma (>5 mm). An increased content of small WSAma (0.25–1 mm) resulted in higher KSC values in WSAmi, whereas medium and large WSAma size-fractions tended to reduce KSC in WSAmi (Table 2). These findings highlight the complex interactions between aggregate size-fractions, aggregate stability, and their capacity to retain carbon within aggregates. Such relationships are consistent with existing literature, which emphasizes that aggregate stability is a key factor in the long-term storage of carbon in soils (He et al., 2023).

Table 2 Correlation coefficient between soil structure parameters and SOM in aggregates

	C_L in				
	WSAma	WSAma >5	WSAma1–5	WSAma0.25–1	WSAmi
KSs	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma	n. s.	n. s.	n. s.	n. s.	0.589
DSAma >5	n. s.	n. s.	n. s.	n. s.	-0.181
DSAma 1–5	n. s.	n. s.	n. s.	n. s.	0.380
DSAma 0.25–1	n. s.	n. s.	n. s.	n. s.	-0.258
DSAmi	n. s.	n. s.	n. s.	n. s.	-0.591**
PAD	0.506*	n. s.	0.507*	n. s.	n. s.
KSw	n. s.	n. s.	0.469*	n. s.	n. s.
WSAma	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma >5	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma 1–5	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma 0.25–1	n. s.	n. s.	n. s.	n. s.	n. s.
WSAmi	n. s.	n. s.	n. s.	n. s.	n. s.

Statistically significant correlations are shown as follows: n. s. p >0.05; * p <0.05; ** p <0.01; *** p <0.001

Continuation of table 2

	C_{org} in				
	WSAma	WSAma >5	WSAma1–5	WSAma0.25–1	WSAmi
KSs	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma >5	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma 1–5	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma 0.25–1	n. s.	n. s.	n. s.	n. s.	n. s.
DSAmi	n. s.	n. s.	n. s.	n. s.	n. s.
PAD	n. s.	n. s.	n. s.	n. s.	n. s.
KSw	0.538*	0.470*	0.584*	0.461	0.521
WSAma	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma >5	-0.497*	-0.537*	-0.500*	n. s.	-0.520
WSAma 1–5	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma 0.25–1	n. s.	n. s.	n. s.	n. s.	n. s.
WSAmi	n. s.	n. s.	n. s.	n. s.	n. s.

	KSC in				
	WSAma	WSAma >5	WSAma1–5	WSAma0.25–1	WSAmi
KSs	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma	-0.851***	-0.818***	-0.690**	n. s.	-0.857***
DSAma >5	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma 1–5	n. s.	n. s.	n. s.	n. s.	n. s.
DSAma 0.25–1	0.499*	0.596**	n. s.	n. s.	0.485*
DSAmi	0.852***	0.818***	0.691**	n. s.	0.856***
PAD	n. s.	n. s.	n. s.	n. s.	n. s.
KSw	n. s.	n. s.	n. s.	n. s.	0.590**
WSAma	n. s.	n. s.	n. s.	n. s.	n. s.
WSAma >5	n. s.	n. s.	n. s.	n. s.	-0.780***
WSAma 1–5	n. s.	n. s.	n. s.	n. s.	-0.478*
WSAma 0.25–1	n. s.	n. s.	n. s.	n. s.	0.768***
WSAmi	n. s.	n. s.	n. s.	n. s.	n. s.

Statistically significant correlations are shown as follows: n. s. p >0.05; * p <0.05; ** p <0.01; *** p <0.001

4 Conclusions

The distribution of individual size-fractions of soil aggregates varied depending on the soil type. Cambisol exhibited the highest aggregate stability and water resistance.

In all soils, the content of SOM was higher in the larger size-fractions of water-stable macroaggregates compared to water-stable microaggregates. Although Chernozems had the highest SOM in soil aggregates, they exhibited the lowest carbon sequestration index indicating that a high organic matter content does not necessarily equate to a high sequestration potential. The highest sequestration index in soil aggregates, particularly in the WSAma >5 mm fraction, was recorded in Calcisols.

Aggregate stability was positively influenced by higher contents of labile carbon, especially in medium-sized macroaggregates (1–5 mm). An increased content of small water-stable macroaggregates (0.25–1 mm) enhanced the carbon sequestration index in water-stable microaggregates, whereas a higher content of large and medium water-stable macroaggregates reduced it. These findings highlight the complex interactions between aggregate size, structural stability, and the capacity of soil to sequester carbon.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Vladimír Šimanský: Conceptualization; Methodology; Supervision; Validation; writing – original draft preparation; writing – review & editing. Martin Juriga: formal analysis; investigation; writing – review & editing.

AI and AI-assisted Technologies use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

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