https://doi.org/10.17221/3/2024-SWR

Soil organic carbon and its labile fractions in the conditions of water erosion on arable land of Chernozems area

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Citation: Balontayová E., Petlušová V., Petluš P., Hreško J., Koco Š. (2024): Soil organic carbon and its labile fractions in the conditions of water erosion on arable land of Chernozems area. Soil & Water Res., 19: 90–99.

Abstract: The depletion of organic carbon in the topsoil and the reduction of the humic horizon leads to a decrease in soil productivity. This study focussed on evaluating the influence of water erosion on the quantity and quality of organic carbon (OC) in the topsoil. The determination of the differences in the OC with dependence on the soil thickness and the role of the soil texture in a depletion of OC in the humic horizon and its labile fractions were studied in four arable land localities (Haplic Chernozem, HC; Eutric Regosol, ER). The following carbon parameters were included: total organic carbon (TOC), labile carbon oxidisable by $KMnO_4$ (C_L), cold and hot water-extractable organic carbons (CWEOCs) and (HWEOCs), respectively. The higher the soil thickness was, the higher the OC contents were at a depth of up to 0.1 m (TOC; r =0.387, $P < 0.01$; C_L; $r = 0.266$, $P < 0.01$), which indicates a more pronounced organic and mineral material washing off. This process was more pronounced on the texturally finer HC than the coarser ER soil. In the case of water-extractable organic carbon (WEOC), the vertical movement was dominant, while in the case of C_L, the horizontal one was dominant. In the case of erosion, the spatial variability of the OC is not only the result of the erosion-accumulation activities, but also from the proportion of the OC forms. The erosion significantly interferes in the stabilisation mechanisms of organic substances, and even also influences one of the strongest factors – the soil texture.

Keywords: carbon fractions; Chernozem; erosion-accumulation processes; Regosol; soil thickness; texture

Water erosion is associated with soil degradation, mainly with the removal of soil particles, their downstream transport as runoff, and, at the end, the accumulation of the carried material in new sites (Polykretis et al. 2023). Humic horizons are reduced and often already removed, and transported material, rich in an organic carbon (OC), covers an original topsoil in the concave sites, resulting in the change of landscape structure (Zádorová & Penížek 2018; Juřicová et al. 2022). Human activities, especially intensive agriculture in the case of Chernozems, rapidly accelerate soil erosion (Borrelli et al. 2017). The intensity of the soil particle transport is negatively correlated with the rate of infiltration, while this

Supported by the Ministry of Education, Research, Development and Youth of the Slovak Republic, Project KEGA 005SPU-4/2022 "Incorporation of contemporary environmental topics into the teaching of soil-related subjects"

https://doi.org/10.17221/3/2024-SWR

process, in addition to the topography (Pavlů et al. 2022; Yu et al. 2023), is also significantly influenced by the soil texture and OC contents (Wei et al. 2019).

Clay and the OC play a key role in improving the soil erosion resistance. In relation to the OC distribution, the silt content is often more important than the clay content (Qin et al. 2022). In general, the proportions of sand and clay influence the cohesion of a soil (Wei et al. 2015), which is an important factor in the case of the soil's mechanical properties. The splash erosion risk decreases in soils in the following manner: sandy > loamy > clay (Zhu et al. 2024). The soil texture also has an indirect effect on the soil crust formation (Li et al. 2023). However, water erosion also results in soil texture degradation (Xing et al. 2023). Finer particles are often washed away and then transported further downstream (Quijano et al. 2020), however, a higher rainfall intensity may result in less selective erosion and lead to a different soil particle distribution (Kuhn & Armstrong 2012). The particle size affects the erosion risk, but the properties of the organic matter importantly change it.

Erosion has a significant impact on the characteristics of the eroded organic matter (Liu et al. 2019). OC is transported preferentially (Holz & Augustin 2021), while most of the transported OC is in the form of particular organic carbon (POC) (Su et al. 2024). It includes particles larger than 20 μm, from larger unchanged pieces of recent organic inputs to smaller organic substances, including those incorporated into the soil aggregate. Soil erosion also has an influence on the chemical composition (Wang et al. 2023) and stability of the OC (Fissore et al. 2017). The OC of eroded soil has higher stability than deposited soil (Liu et al. 2019; Li et al. 2022). Approximately 20% of the OC already decomposes during the transportation process (Berhe et al. 2018). OC is initially transported as non-protected, until later as protected (Campo et al. 2022). Chemically protected OC is transported to a longer distance than the physically, mainly OC protected in the soil aggregates. Then, the result of the soil erosion is up to 25–36% and of decomposition 33–45% OC losses (Liu et al. 2021), which, in combination, represent huge losses in the OC, mainly from arable land. So, erosion significantly affects the characteristics of the mechanisms of OC stabilisation, which is the next issue for erosion effect studies.

In the case of dissolved organic carbon (DOC), its concentration is higher at the beginning of the runoff and later, if diluting occurs (Mchunu & Chaplot 2012). Water-extractable organic carbon (WEOC) is a part of DOC and it is the most active and mobile fraction of OC, which reacts very sensitively to water erosion, while more pronounced fluctuations in the WEOC contents are below 0.2 m (Yao et al. 2023). Rizinjirabake et al. (2019) did not observe more pronounced differences in the WEOC in the upper slopes, in concave and convex areas or places of topsoil accumulation conditioned by erosion. They are influenced rather by soil respiration (Fissore et al. 2017). Soil redistribution, in connection with changes in the WEOC, thus also has an impact on the CO_2 emissions (Gao et al. 2020). A higher intensity of OC mineralisation occurs on the eroded surfaces since the labile OC is removed by erosion (Qiu et al. 2021). However, in the places of OC deposition, the eroded OC is buried, and the formation of organo-mineral complexes is supported, which leads to the stabilisation of OC (Dalzell et al. 2022; Lv et al. 2023), and thus to its long-term fixation (Zeng et al. 2024) and eventually to its sequestration.

Chernozems are one of the soils that is most seriously threatened by water erosion. In these soils, at a depth of up to 1 m, the largest store of OC exists in the world (250–320 t/ha) (Buryak et al. 2023). Drewnik and Żiła (2019) refer to Regosol as a post-chernozem, the final stage of extreme slope erosion. On the other hand, colluvial soil is considered by Zádorová and Penížek (2018) to be a thickened Chernozem, as the soil developed in the local depressions and foot slopes. Zádorová et al. (2023) consider it an important soil unit in the erosion-affected landscape. All of the mentioned soils, which developed on the same substrate, were included in this study.

The aim of this study was to evaluate the influence of water erosion on the organic carbon. The quantity of losses of the total or stabile OC is more often presented than the changes in labile fractions, probably because of their characteristics. Therefore, the aims of this study were: (*i*) to determine the differences in the OC with dependence on the soil thickness; (*ii*) to evaluate the reaction of different labile fractions of OC on the erosion-accumulation processes; (*iii*) to identify the importance of the soil texture in the removal of the OC by water erosion.

MATERIAL AND METHODS

Study sites. The localities of soil sampling were situated on the Danube Lowland in the areas of chernozem formation on arable land (Figure 1A–D).

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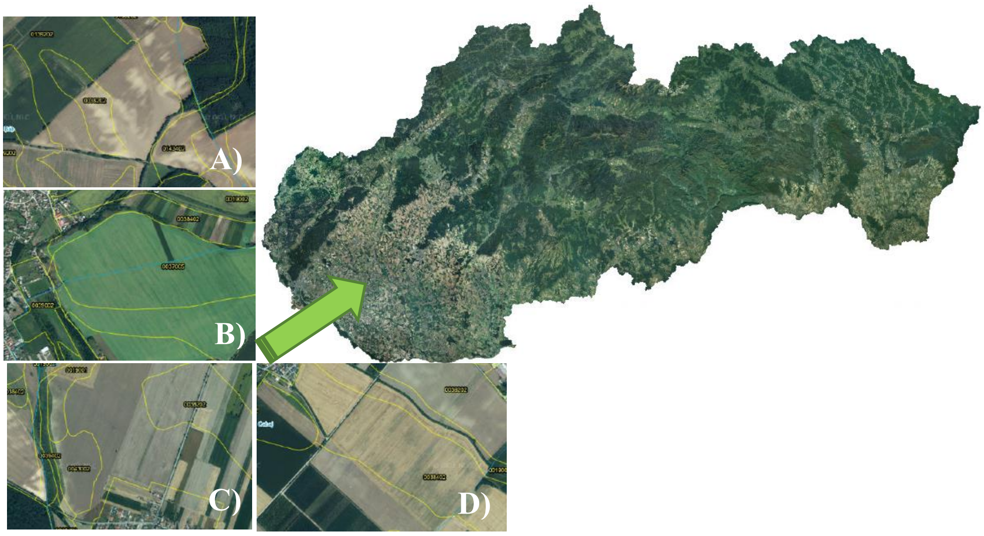

Figure 1. Map of the soil sampling areas: Báb (A), Horná Kráľová (B), Cabaj-Čápor – part Pereš (C), Cabaj-Čápor (D) map source: www.podnemapy.sk

The geological substrate was created mainly with Quaternary and Neogene sediments. The natural vegetation, before conversion to arable land, was represented by oak forests. The relief of the studied areas is undulate and without any important influence of underground or flowing water. All the fields were in real production conditions, where cereals (75%) and oilseeds (20%) were dominantly grown on them. The balance of the OC inputs was positive on each of the fields. All four localities were in warm to very warm and very dry climate regions, with an average annual temperature of 10.9 °C and an annual rainfall of 609 mm over the last 3 years (Faško 2023).

At each locality, the soil samples were collected in the spring in a network of equilateral triangles (with an arm of 100 m) depending on the configuration of the terrain numbering 40–62 points (204 sampling points in total). At each sampling point, the depth of the soil profile (soil thickness, humic horizon and substrate) was measured and soil samples were taken to a depth of 0.1 m (Table 1). The mentioned depth was chosen based on the thickness of the washed humic horizon and then the determination of the shallowest of them. The soils in these localities were classified as follows: 136 probes as a Haplic Chernozem (HC) and 44 probes as a Eutric Regosol (ER) according to the World Reference Base for Soil Resources (WRB 2015), with a current identification of alluvium (Colluvisol; CO) in 24 probes. The HC was characterised by average values of the total organic carbon (TOC) of 18.69 g/kg, pH_{KCl} of 6.64, CEC of 288.25 mmol/kg, and physical clay of 40.81%; the ER was characterised by average values of the TOC of 13.77 g/kg, pH_{KCl} of 6.34, CEC of 216.44 mmol/kg, and physical clay of 29.14%; the CO was characterised with a TOC of 29.64 g/kg, pH_{KCl} of 7.09, CEC of 295.37 mmol/kg, and physical clay of 48.10%.

Soil sampling and laboratory analysis. Soil samples were dried at room temperature and sieved (< 2 mm and < 0.25 mm sieves). The OC parameters

Table 1. The characteristics of the basic evaluated parameters on the studied localities to a depth of 0.1 m

Locations	TOC (g/kg)	pH_{KCl}	CEC (mmol/kg)	Physical clay (< 0.01 mm) (%)	Soil thickness (up to the substrate) (m)
BB	14.16 ± 3.22	6.54 ± 0.77	310.38 ± 30.46	39.81 ± 3.04	0.54 ± 0.32
CC	17.43 ± 2.79	6.19 ± 0.83	358.50 ± 94.44	43.08 ± 3.58	0.60 ± 0.28
CP	17.85 ± 3.20	6.14 ± 1.14	387.16 ± 64.67	40.71 ± 4.85	0.54 ± 0.27
HK	20.17 ± 2.99	6.59 ± 0.12	395.37 ± 7.59	35.18 ± 6.68	0.53 ± 0.23

BB – Báb; CC – Cabaj-Čápor; CP – Cabaj-Čápor – part Pereš; HK – Horná Kráľová; TOC – total organic carbon; CEC – cation exchangeable capacity

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(TOC; labile carbon oxidisable by potassium permanganate, C_L; WEOC) and texture composition were determined in the soil samples. The TOC was determined by $K_2Cr_2O_7$ oxidation (wet combustion), according to Orlov and Grišina (1981). The C_L was determined according to Loginov et al. (1987) with the subsequent calculation of the carbon lability (L_C) according to Blair et al. (1995). The cold and hot water-extractable organic carbon (CWEOC and HWEOC), respectively, were determined according to Ghani et al. (2003), with the final determination of organic carbon determined by wet combustion (Orlov & Grišina 1981). The soil texture was determined according to the pipette method (van Reeuwijk 2002). Soil was treated to remove the carbonates and organic matter. After dissolution of $CaCO_3$ with 2 mol of HCl/dm^3 and oxidation of the organic carbon with 30% H_2O_2, it was followed by repeated washing and finally the samples were dispersed using $Na(PO_3)_6$. The silt, sand, and clay fractions were determined. The soil pH was potentiometrically measured in a supernatant suspension of a 1 : 2.5 soil : liquid mixture (1 mol/dm^3 of KCl). The cation exchangeable capacity (CEC) was determined according to the Pfeffer method (Jackson 2018).

Statistical analysis. The obtained data were analysed using Statgraphic Plus (Ver. 5.1, 2008) and Centurion (Ver. 17) statistical software. A multifactor analysis of variance (ANOVA) model was used for the individual treatment comparisons at $P < 0.05$, with separation of the means by the least significant difference (LSD) multiple-range test ($n = 204$). A correlation analysis was used to determine the relationships between the organic carbon and its labile fractions, particle size distribution, and soil thickness. The significant Pearson correlation coefficients were tested at $P < 0.05$ and $P < 0.01$.

RESULTS AND DISCUSSION

The total soil thickness (Figure 2B) in all the localities was closely related with the TOC (Figure 2C) and clay contents (Figure 2D) at a depth of up to 0.1 m. The distribution of OC in the soil is a reflection of the properties of a given ecosystem, including the differences in the carbon inputs in the shallow and deep soils and its subsequent redistribution by water flow (Souza et al. 2023). On the soil surface, the transport of fine particles occurs (Quijano et al. 2020), so, at the same time, the movement of the particular organic matter (POM) (Rachels et al. 2020; Su et al. 2024), which primarily manifests at a depth of up to 0.1 m in the short time.

The soil thickness was the highest in the depressed positions, and, on the contrary, the soil was the shallowest on the slopes with a more pronounced inclination, which are the initial manifestations of water erosion that, in this case, also lead to the mosaic-like discontinuity of the soil cover of original chernozems (Labaz et al. 2019). In addition to the HC, ER was

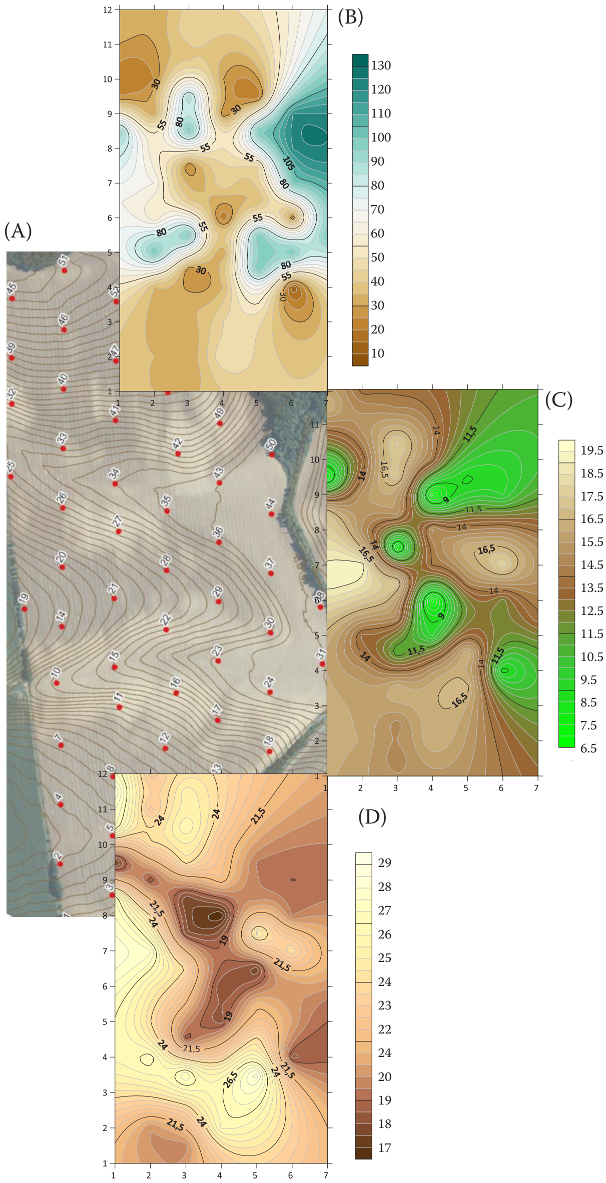

Figure 2. Map of the Báb locality: example of the soil probe distribution in the Báb locality (A), soil thickness (cm) (B), total organic carbon content (g/kg) (C), clay content (%) (D)

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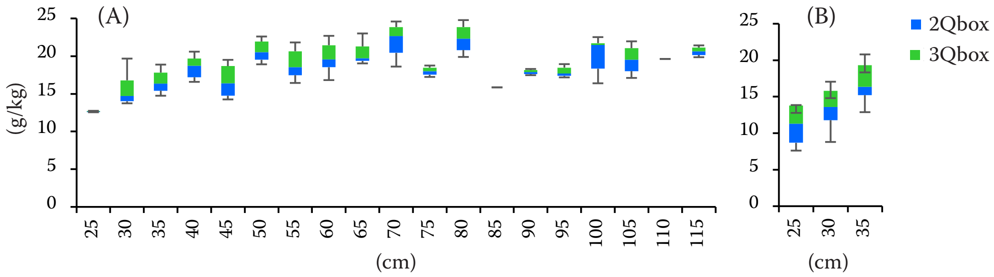

Figure 3. Average total organic carbon (TOC) at all the localities at a depth up to 0.1 m with dependence on the soil thickness: Haplic Chernozem (A) and Eutric Regosol (B)

also at the monitored sites, and, simultaneously, Colluvisol was also identified in the accumulation zones.

The higher soil thickness (HC, ER), the higher the TOC content was (r =0.372, P < 0.01; r = 0.436, P < 0.01) at a depth of up to 0.1 m in all the localities and at all the sampling points (Figure 3). Differences also occurred between the soils. In the case of ER, these differences were more pronounced than in the HC, while the ER had lower TOC and clay contents at a depth of up to 0.1 m. In the case of clay, in relation to the soil thickness, more significant differences were not observed in either the HC or ER, in spite of the fact that its content was in correlation with the TOC (r =0.195, P < 0.05; r = 0.301, P < 0.05) (Figure 4). In spite of the same substrate of both soils, the spatial soil cover was substantially variable (Chodorowski et al. 2019). In the case of the shallow ER, the differences were more pronounced, which was the soil of the more eroded sites, but in the case of deeper soils, more pronounced differences were not recorded. Since it is intensively cultivated arable land, these differences are the result of human-accelerated erosion (Borrelli et al. 2017; Smetanová et al. 2017). The humic horizon of HC is deeper than 0.1 m, therefore the differences in this depth in the same locality with the same management system are not the result of differences in the humic horizons, but the action of flowing water, which drags down the organic and clay particles. This causes some places to be depleted of the organic and clay particles, and, on the contrary, other places to become a place of their accumulation.

The movement of organic particles occurs both vertically (in the soil profile) and horizontally (along the slope). The vertical profile of the OC is also dynamic and constantly changing in reaction to erosion (Jague et al. 2016). In the case of texturally coarse soil, the vertical movement is dominant, while, in the case of texturally finer soil, the horizontal movement is dominant. In clay soils, the OC removal is a more pronounced than in sandy soils (Manninen et al. 2023), which was also reflected in the differences between the HC and ER. In the case of the ER, the significant differences were recorded in the C_L. This fraction also includes the POM that assumes the dominance of the horizontal movement, which is confirmed by the fact that the C_L content at a depth of up to 0.1 m also increases with the soil thickness increase (Figure 5A). The coarser fractions of the soil organic matter are more intensively influenced by erosion. In the zones of the highest accumulation, the finer particles are dominant, which, however, are not only of a primary (moved without any change) but also of a secondary (formed when moving down the slope from larger

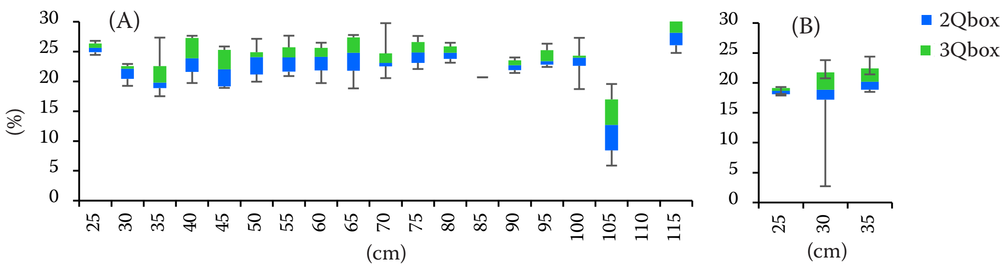

Figure 4. Average clay content at all the localities at a depth up to 0.1 m with dependence on the soil thickness: Haplic Chernozem (A) and Eutric Regosol (B)

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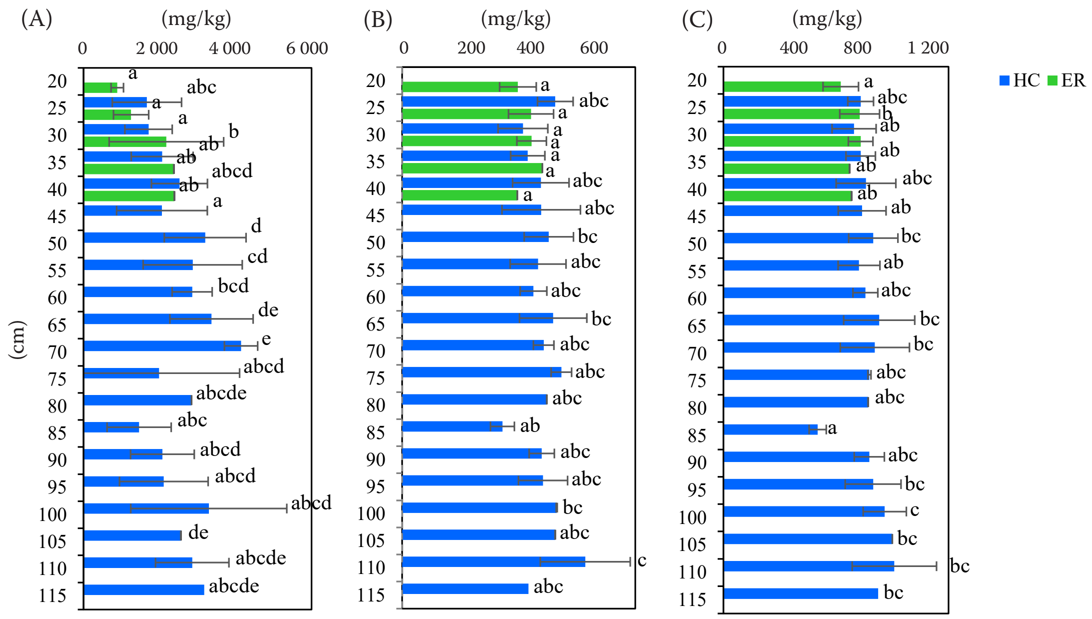

Figure 5. Average contents of the labile carbon fractions at all the localities with dependence on soil thickness: labile carbon oxidisable with $KMnO_4$ (A), cold water extractable organic carbon (B), hot water extractable organic carbon (C) HC – Haplic Chernozem; ER – Eutric Regosol; different letters between the factors show statistically significant differences ($P < 0.05$) – LSD test

particles) origin. The result is a change in the proportionality of the size particles, which is not only the question of the quantity, but also the quality of the OC (He et al. 2023). In the case of the HC, it was confirmed to a soil thickness of 0.4 m that the higher the soil thickness, the higher the C_L content is at a depth of up to 0.1 m. At a higher soil thickness, there was a fluctuation in its contents, which is already, in these cases, probably the result of a combination of the accumulation and removal of the surface layer of the soil in the past. The mentioned phenomenon is also strengthened by the intensity of the covering of the original topsoil with a new alluvial layer (Juřicová et al. 2022). The CWEOC and HWEOC contents were more balanced since, due to their solubility, their vertical movement are more pronounced compared to the C_L. The dissolved OC content not only increases with the depth of the soil profile, but, in the topsoil, it is also easily accessible to microorganisms (Wang et al. 2023). The mentioned differences are markedly influenced by erosion-accumulation processes, mainly by the location on the slope in relation to its inclination and length, which influence the rate and intensity of the water action. Singh and Benbi (2018) recorded the highest TOC contents at the top slope, mainly of the recalcitrant fraction, followed by the lower parts, and the lowest contents were in the middle positions of the slope, so with the smallest soil thickness, which is consistent with our results. In the case of the highest soil thickness, simultaneously, the accumulated soil layer manifests in a very high quality. This is also proven by the fact that, in the case of CWEOC (Figure 5B) and HWEOC (Figure 5C) in the water-extractable fractions of the carbon, these differences at a depth of up to 0.1 m are minimal. In the case of the HC, it is not just about a more marked vertical shift in the water-extractable OC fractions, but due to the higher TOC and clay contents, which contribute to water retention, the more pronounced their contents fluctuate in the soil profile. The spatial variability of the SOC is, thus, not only in correlation with the geomorphological variables (among others, the topographic moisture, index of sediment transport or tillage erosion) (Gómez et al. 2023), but also with the current properties of the given soil.

The soil texture plays an important role in the soil's resilience to erosion (Lal 2001). Most of the OC is bound in the silt fraction (Christensen & Sörensen 1985). In the case of both the HC and ER (Table 2), negative correlations of C_L and L_C with the silt fraction and a positive correlation with the clay fraction were recorded. The stabilising effect of clay is known (Wang et al. 2022), while, in this case, the given correlation rather indicates a mechanism

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Table 2. Correlations between the parameters of the organic carbon and soil texture, the soil thickness of the Haplic Chernozem and Eutric Regosol

	TOC	C_L	L_C	CWEOC	HWEOC
Haplic Chernozem					
Soil thickness	0.372**	0.254**	ns	0.172*	0.241**
Clay	0.195*	0.292**	0.325**	ns	ns
Silt	–0.250**	–0.421**	–0.433**	ns	–0.289**
Sand	ns	0.192*	0.183*	ns	0.305**
Eutric Regosol					
Soil thickness	0.436**	0.458**	0.373*	ns	ns
Clay	0.301*	0.399**	0.509**	ns	ns
Silt	ns	–0.365*	–0.440**	ns	ns
Sand	ns	ns	ns	ns	ns

TOC – total organic carbon; C_L – labile carbon oxidisable $KMnO_4$; L_C – carbon lability; CWEOC – cold water extractable organic carbon; HWEOC – hot water extractable organic carbon; *,***P* < 0.05, 0.01; ns – not significant; the values are presented as correlation coefficients (i.e., without units); the values processed (including units) were: L_C (without units); C_L, CWEOC, and HWEOC (mg/kg); TOC (g/kg); clay, silt, and sand (%)

of physical stabilisation of labile forms of OC, as the higher content of labile carbon and higher lability of OC were at a higher clay content and a lower proportion of silt fraction. Qin et al. (2022) found out the greater impact of silt than clay on the OC stabilisation, which is consistent with our results, indicating that a higher amount of chemically stabilised OC is thus bound in silt. In the case of the ER, the intensity of the soil profile washing is higher, therefore the correlation with water-extractable fractions at a depth of up to 0.1 m was not recorded (Table 2). In the case of the HC, a negative correlation between the HWEOC and the silt fraction was recorded, which means the same as in the case of the C_L. The HWEOC includes a huge number of microbial cells, which are released into the solution at the extraction temperature of 80 °C (Gregorich et al. 2003).

A positive correlation with the sand fraction, thus, reinforces the assumption of a more pronounced influence of the edaphic factor, which is conditioned by water erosion in the given ecosystem and has a stabilising effect on the OC (Li et al. 2022). The mentioned authors also showed the higher thermal stability of the OC of eroded soils than soils with a more marked deposition, which is in consistent with our findings of higher contents of labile fractions in the OC in the deeper soils. Overall, the erosion also influences the characteristics of the mechanisms of the OC stabilisation (Dalzell et al. 2022).

CONCLUSION

The amount of transported organic material also depends on the form of OC, or its stability. The movement of the labile insoluble fractions of organic particles is more pronounced, which is evidenced by the higher C_L contents in the thicker soils and in the accumulation zones. In the case of the soluble OC fractions, a part of them is already decomposes at the beginning of their journey, another part, due to their characteristics, infiltrates with the rainfall into the soil profile, and the rest is deposited as a part of the new alluvium. The CWEOC and HWEOC contents in the accumulation zones, therefore, significantly fluctuate at a depth of up to 0.1 m and do not always correspond with the soil thickness. Due to the diversity of the OC forms and their stability, the result of the erosion-accumulation processes is also due to their significant spatial variability, which, in the case of labile OC forms, does not completely copy the resulting effect of erosion in the given landscape. The study of the influence of erosion on the OC at a depth of up to 0.1 m is, thus, a suitable tool for assessing the response to the given processes and makes it possible to predict the longer-term characteristics of these processes. In order to study the erosion effect for a longer period, it is necessary to make the assessments at a greater depth, regardless of the mix of horizons in the examined sample. The soil texture is an important factor that, through the water, also influences the redistribution of the OC in the soils affected by water erosion.

https://doi.org/10.17221/3/2024-SWR

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Received: January 12, 2024
Accepted: February 26, 2024
Published online: March 22, 2024