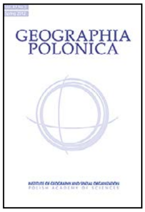

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SOIL STRUCTURE AND AGGREGATE STABILITY OF A-HORIZONS IN DIFFERENT SOIL TYPES ACROSS THE NITRA VALLEY SLOPE, WESTERN SLOVAKIA

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Abstract

The aim of the study was to identify the impact of the basic soil properties and slope inclination on the distribution and stability of water-stable aggregates in three different land uses (deciduous forest, vineyard, arable soil) across three soil types (Luvic Chernic Phaeozem, Eutric Cambisol, Vermic Chernozem) on slopes in the Nitra Valley, western Slovakia. The analysis revealed that soil type significantly influences aggregate stability and soil structure vulnerability, while soil depth and organic carbon content do not. Changes in primary soil organic matter affected soil aggregation. Increased mineralization of soil organic matter (SOM) supported the formation of primarily large water-stable macro-aggregates (WSAma) > 3 mm, whereas the the immobilization of organic carbon in SOM led to the formation and stabilization of smaller WSAma 1-0.25 mm and water-stable micro-aggregates. Cambisol exhibited the highest stability in both dry and wet conditions as well as the lowest vulnerability of soil structure.

Keywords

aggregate stability • soil structure vulnerability • soil types • humus horizon • soil organic matter • human activity

Introduction

The area of Slovakia is characterized by a more pronounced altitudinal than latitudinal zonation, which results from a relatively varied alternation of soils with increasing altitude of the territory (Bedrna & Jenčo, 2016). In addition, the character of the climate in a sloping terrain can condition the formation of complexes of zonal and azonal soils, which are often eroded up to the soil-forming substrate. Soils with more favorable physical properties and a higher supply of soil organic matter resist erosion processes within soil complexes (Zhou et al., 2024). Inadequate human intervention in the soil environment accelerates soil erosion and transformation (Affek, 2019; Affek et al., 2019; Bucała-Hrabia, 2023; Wang et al., 2024). In this context, soil structure is vital as the most critical basic physical soil property and an important soil quality indicator (Slowińska-Jurkiewicz et al., 2012; Basset et al., 2023; Halder et al., 2024). A change in the state of the soil structure usually also induces a shift in other soil properties. The soil structure is influenced by a whole complex of external and internal factors (Bronick & Lal, 2005; Šimanský et al., 2019), among which there are numerous interactions (Wang et al., 2019). The basic unit of the soil structure is the soil aggregate. Primary peds are relatively permanent aggregates no longer naturally divided into smaller soil units. On the contrary, they can be combined into larger units – aggregates of higher orders (Young & Warkentin, 1975) and thus create soil structure – hierarchical theory (Oades & Waters, 1991). Soil aggregates are the product of the microbial community, soil organic and mineral components, and the action of the plant community and ecosystem. Additionally, they are essential for soil water movement and retention, soil aeration, erosion reduction, root system development, and microorganism activity (Tate, 1995; Bochenek & Kijowska-Strugała, 2021; Kruczkowska et al., 2023). A higher content of water-resistant aggregates generally improves soil structure and reduces soil erodibility (Six et al., 2004; Šimanský et al., 2023). As stated above, human activities can alter the soil structure. Intensive tillage reduces aggregate stability; however, sustainable soil management practices can improve the soil structure (Jonczak et al., 2022; Šimanský et al., 2023) while simultaneously supporting communities of soil organisms that significantly influence it (Regulska et al., 2024). Considering the various factors and their interactions that affect aggregate stability, it is understandable that aggregate stability varies according to soil type, even within specific soil horizons (Bryk, 2016) and land management practices (Šimanský & Bajčan, 2014; Šimanský et al., 2023). The development and eventual stabilization of soil aggregates is closely linked to the type of soil. For instance, the process of aggregate formation in Andisol (Asano & Wagai, 2014) differs significantly from that in Oxisol (Field et al., 2006). As Fulajtár (2006) states, the B-horizons of the Solonetzs soils are characterized by the formation of columnar structure. For example, the eluvial horizons of Luvisols have a platy structure, while the B-horizons of Luvisols exhibit a prismatic blocky structure, and the A-horizons of Chernozems show a moderate granular structure. Soil organic carbon is the binding agent of soil aggregates (Six et al., 2004; Bronick & Lal, 2005; Šimanský et al., 2021; Halder et al., 2024) and affects the water stability of aggregates by decreasing their wettability and increasing their mechanical strength (Onweremadu et al., 2007). Therefore, understanding the relationship between organic carbon and aggregates is crucial in defining soil quality and fertility. The objectives of this study were: (1) to examine how soil structure is affected by different soil types (in A-horizons) along a slope, (2) to determine the influence of soil depth (thickness of A-horizons) on soil structure stability and vulnerability, and (3) to investigate the relationships between soil organic carbon content and soil structure.

Materials and methods

Study site

This study was conducted in Dražovce near Nitra, Slovakia (Fig. 1). The area is a zone with a moderately warm climate with a mean annual temperature oscillating about 7.5-10°C. July is the hottest month, with a mean temperature of 16-18°C, and January is the coldest one, with temperatures of -2 to -4°C. The mean annual rainfall is 550-750 mm (Repa & Šiška, 2004). Slopes of the Tribeč range and higher parts of the Nitra River valley are covered with colluvial deposits built of weathered Carpathian rocks and also with a widespread mantle of Quaternary silty-loamy aeolian loess sediments accumulated in periglacial conditions of the last glaciation (Hreško et al., 2006). The soil profiles studied in this work form a diversified sequence concerning various environmental and anthropogenic factors, and they are localized at the middle part of land use-litho-toposequence – soils of the Nitra Valley slope. According to WRB (IUSS Working Group WRB, 2015), the soils have been classified as follows: (1) Luvic Chernic Phaeozem (Loamic), (2) Eutric Cambisol (Colluvic, Humic, Loamic), and (3) Vermic Chernozem (Aric, Colluvic, Loamic, Loaminovic, Pachic). The basic physical and chemical properties of the upper and second horizons of studied soils are summarized in Tab.1.

Land use of the studied soils

Steep mountain slopes between 300 and 200 m a.s.l. were inclined ca. 8-30° and overgrown with deciduous forest dominated with Turkey oak (*Quercus cerris*) and maple (*Acer* sp.) with an admixture of single pines

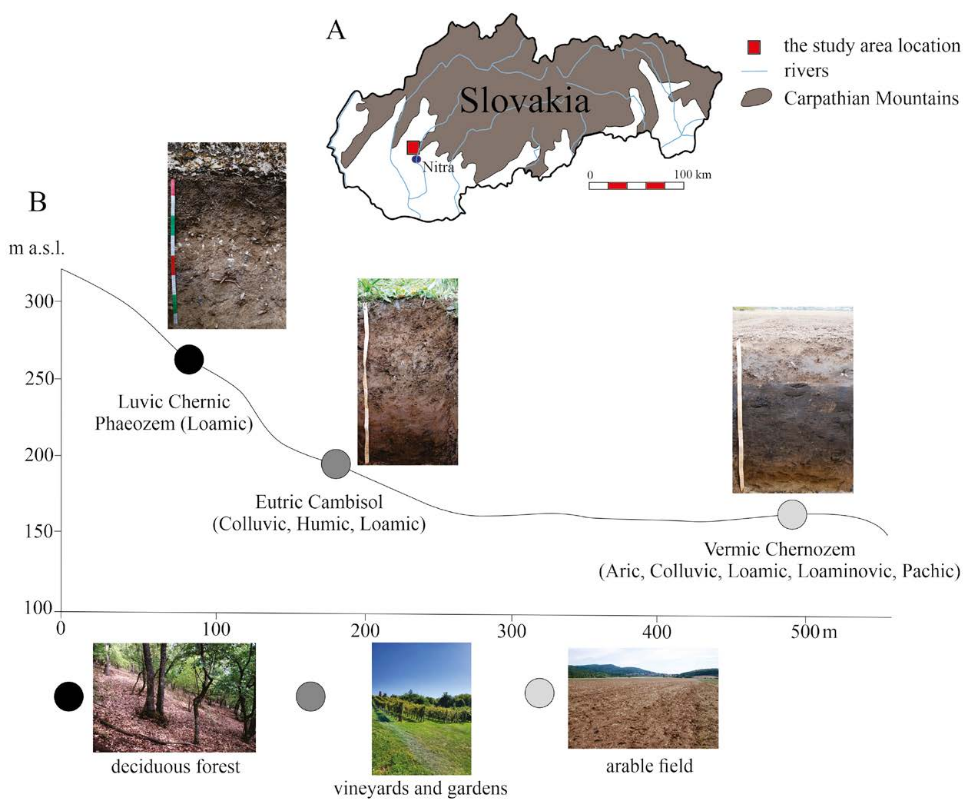

Figure 1. Location of the study area – A; soil profiles location along the transect – B

Table 1. Physical and chemical properties of the studied soils (Jankowski et al., 2018)

Soil type	Horizon	Soil depth [cm]	Textural class	Sand	Silt	Clay	$CaCO_3$	SOC	TN	C/N	pH_{KCl}
				[%]			[g/kg]				
Luvic Chernic **Phaeozem** (Loamic)	A1	0-21	SiL	26	57	17	17	48.7	4.4	11	7.1
	A2	21-35	SiL	31	62	7	16	26.2	2.6	10	7.2
Eutric **Cambisol** (Colluvic, Humic, Loamic)	A1	0-13	SiCl	11	58	31	17	16.6	0.9	19	7.3
	A2	13-30	SiCl	11	56	33	17	9.1	1.1	9	7.4
Vermic **Chernozem** (Aric, Colluvic, Loamic, Loaminovic, Pachic)	Ap	0-27	L	28	46	25	-	14.3	0.7	20	6.4
	A	27-63	SiL	13	51	26	2	13.6	0.7	20	8.1

artificially planted by man (soil classified based on morphological characteristic as Phaeozem). Lower, more gentle parts of slopes (with slope reduction of 5-15°) lying ca. 200-180 m a.s.l. are managed as vineyards and gardens (Cambisol). The soil probe was excavated in a productive vineyard between vine rows, covered with grass strips due to intense erosion for the past 25 years. Soil management practices in the vineyard included cut-down of the grasses in the inter-row spaces (on average three times per year), with the phyto mass remaining on the surface in the form of mulch. No fertilization has been applied in the vineyard for several seven years. The flat and undulated surfaces of the loess terrace (Chernozem) and colluvial cone spread at 170-150 m a.s.l. are intensively used as arable fields. Conventional practices, based on intensive tillage and fertilization, are applied, including annual plowing with a plow to a depth of 25 cm. Samples were collected after the harvest (wheat was grown in the field), with rapeseed as the forecrop.

Soil sampling and analysis

Soil samples for the analysis of physical and chemical properties were collected from all soil horizons in each profile along the middle part of the slope from the Tribeč Mountains to the Nitra River Valley. Undisturbed soil samples for soil structure analysis were collected from the first two A horizons of each soil profile (Tab. 1). Soil basic properties were determined using standard analytical methods: soil pH in a 1:2.5 soil/1 mol/L KCl mass ratio by the pH meter – potentiometrically; content of carbonates ($CaCO_3$) based on the CO_2 evolution after reaction with HCl (diluted with water in a 1:3 ratio) – volumetric method using a Jankov calciminer; soil organic carbon (SOC) was measured using the wet combustion method – oxidation of soil organic matter by a mixture of 0.07 mol/L H_2SO_4 and $K_2Cr_2O_7$ with titration using Mohr's salt, and soil texture – pipette method (Hrivňáková et al., 2011). Before water-stable aggregates were determined, all soil samples were sieved to provide a range of aggregate sizes (> 7; 7-5; 5-3; 3-1; 1-0.5; 0.5-0.25, and < 0.25 mm). This study used water-stable aggregates (WSA) sieved by the Baksheev device. A detailed description of this methodological procedure is given in Šimanský (2014). The size fractions of water-stable macro-aggregates (WSAma) were the following: > 5; 5-3 (large), 3-2; 2-1 (meso), 1-0.5; 0.5-0.25 (small), and < 0.25 mm were water-stable micro-aggregates (WSAmi).

Aggregate stability was expressed in the mean weight diameter (MWD) from a range of aggregate sizes provided by dry sieving (MWD*d*) as well as by wet sieving (MWD*w*) and calculated by the following equations:

$$MWD_d = \sum_{i=1}^{n} x_i w_i \qquad (1)$$

where:

MWD_d – is mean weight diameter of aggregates for dry sieving (mm), *xi* – is mean diameter of each size fraction (mm) and

wi – is portion of the total sample weight occurring in the corresponding size fraction, and

n – is the number of size fractions.

$$MWD_W = \sum_{i=1}^{n} x_i WSA \quad (2)$$

where:

MWD_w – is mean weight diameter of water stable aggregates (mm),

xi – is mean diameter of each size fraction (mm) and

WSA – is portion of the total sample weight occurring in the corresponding size fraction, and

n – is the number of size fractions.

The vulnerability of soil structure was expressed in the index of vulnerability (Kv) calculated by the following equations:

$$K_v = \frac{MWD_d}{MWD_w} \quad (3)$$

Statistical analysis

A two-way ANOVA was performed on soil structure parameters to evaluate the effects of soil type, soil depth and their interaction on these measured properties. Dependencies between the parameters of soil structure and the chemical properties of the soil were evaluated using a simple correlation matrix and were expressed by a Pearson's correlation coefficient at the different probability levels, with a significance level of $p < 0.05$.

Results

Distribution of water-stable aggregates

The water-stable aggregate (WSA) size distribution was significantly affected by soil type, not soil depth. The soil type × soil depth showed no significant effects on WSA content (Tab. 2). The contents of WSA in the Chernozem was significantly different from that in the Phaeozem and Cambisol (Fig. 2). Meso- and small-aggregates WSAma (2-0.25 mm) and micro-aggregates WSAmi of Chernozem accounted for the most significant two proportions in this soil type, accounting for 8-34% and 12-22% of the total soil volume, respectively. However, large WSAma

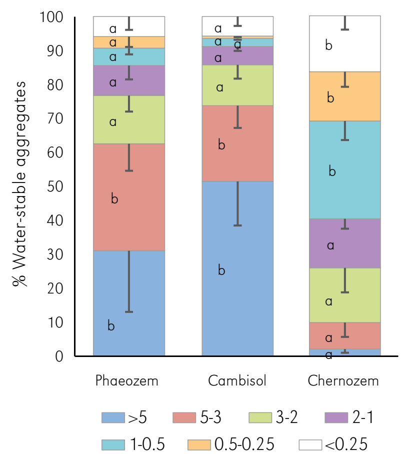

Figure 2. Individual size fractions of water-stable aggregates according to Tukey's procedure. Identical letters indicate homogeneous groups at the p < 0.05 significance level

Table 2. Results of two-way ANOVA for soil structure depending on soil type and soil depth

	Size distribution of water-stable aggregates (mm)							MWDd [mm]	MWDw [mm]	Kv
	large macro-		meso macro-		small macro-		micro-			
	> 5	5-3	3-2	2-1	1-0.5	0.5-0.25	< 0.25			
Soil type	**0.0117**	**0.0037**	**0.6703**	**0.0182**	**0.0002**	**0.0158**	**0.0025**	**0.0252**	**0.0017**	**0.0010**
Depth	0.8158	0.3089	0.5763	0.6583	0.9190	0.4847	0.5557	0.7673	0.9418	0.2567
Soil type x Depth	0.9466	0.2518	0.7307	0.4418	0.7455	0.7608	0.5213	0.6174	0.7814	0.2131

Bold – indicates a significance level of $p < 0.05$; MWDd – mean weight diameter of aggregates for dry sieving; MWDw – mean weight diameter of water stable aggregates (mm); Kv – index of vulnerability.

(> 3 mm) accounted for the most diminutive proportions in Chernozem compared to other soil types. On the other hand, the WSAma fraction of > 3 mm (large) covered the most significant proportion (62~73%) in these soil types. In contrast, the meso and small WSA fractions (2-0.25 mm) and WSAmi occupied the least, from 0.7~9% and ~6%, respectively.

Soil structure stability and vulnerability

Several parameters are used to assess the stability and vulnerability of the soil structure. In the case of this study, aggregate stability and soil structure vulnerability were evaluated using MWDd, MWDw, and Kv in A-horizons of investigated soil types. Soil type had the most significant effect, while depth and the soil type x depth interaction had no statistically significant impact on the stability and vulnerability of the soil structure (Tab. 2). The A-horizons of the soil types differed depending on the assessed parameter of soil structure (Fig. 3). The A-horizons of both Cambisol and Chernozem had almost the same MWDd values, while the Phaeozem had statistically significantly lower MWDd values. The A-horizon of the Chernozem had statistically significantly lower MWDw values compared to the A-horizons of the Phaeozem and Cambisol. Additionally, the A-horizon of the Chernozem exhibited almost three times higher soil structure vulnerability compared to the A-horizons of the Phaeozem and Cambisol (Fig. 3).

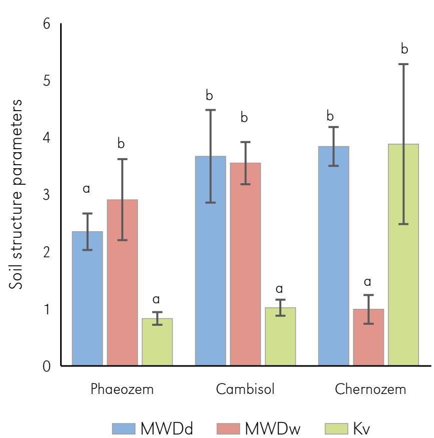

Figure 3. Parameters of soil structure stability and vulnerability. According to Tukey's procedure, letters indicate homogeneous groups at $p < 0.05$ significance level. Abbreviations are explained in Tab. 2.

Correlation coefficients between soil properties and soil structure

Soil organic carbon did not affect aggregation nor the stability and vulnerability of the soil structure. Total nitrogen content was related to large WSAma (5-3 mm) positively and MWDd negatively. The C/N ratio correlated negatively with large WSAma (> 3 mm) and positively with small WSAma (1-0.5 mm) and WSAmi. Increasing the C/N ratio resulted in an increase of MWDw, and conversely, narrowing the C/N ratio reduced the vulnerability of the soil structure. A positive correlation was found between carbonate content and large WSAma (> 5 mm). However, carbonates were negatively correlated with meso WSAma (2-1 mm), small WSAma (1-0.25 mm), and WSAmi. High carbonate content reduced the vulnerability of soil structure and increased MWDw. The silt content was positively correlated with the fraction of large WSAma (5-3 mm) and negatively with small WSAma (1-0.5 mm) and WSAmi. Higher silt content improved the water resistance of the aggregates by increasing the MWDw and reducing the Kv values. Higher clay content had a positive effect on MWDd.

Discussion

Changes in soil structure

In the studied area, the soil sequence Phaeozem-Cambisol-Chernozem may be considered as land use-litho-toposequence (Jankowski et al., 2018). These soils developed on relocated weathered material (Phaeozem) and loess relocated by slope processes (Cambisol, Chernozem). In this case, the soil-forming substrate was a fundamental factor in the soil-forming process. According to Jankowski et al. (2018), the natural features of analyzed soils were strongly transformed by intensive land

Table 3. Pearson's correlation coefficients between soil properties and soil structure

	Size distribution of aggregates							MWDd	MWDw	Kv
	large macro-		meso macro-		small macro-		micro-			
	> 5	5-3	3-2	2-1	1-0.5	0.5-0.25	< 0.25			
SOC	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.678*	n.s.	n.s.
N	n.s.	0.618*	n.s.	n.s.	n.s.	n.s.	n.s.	-0.660*	n.s.	n.s.
C/N	-0.601*	-0.606*	n.s.	n.s.	0.699*	0.603*	0.733**	n.s.	-0.676*	0.668*
pH	n.s.	n.s.	-0.674*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$CaCO_3$	0.950***	n.s.	n.s.	-0.906***	-0.877***	-0.894***	-0.820**	n.s.	0.960***	-0.768**
Sand	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.592*	n.s.	n.s.
Silt	n.s.	0.801**	n.s.	n.s.	-0.770**	-0.623*	-0.587*	-0.654*	0.641*	-0.733**
Clay	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.799**	n.s.	n.s.

Statistically significant correlations are shown as follows: n.s. $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Abbreviations are explained in Tab. 2.

use, mostly agro-denudation. Soil structure results from external and internal factors and their mutual interactions (Bronick & Lal, 2005; Halder et al., 2024). It can be significantly modified through agrotechnical operations (Šimanský et al., 2023). The A-horizons of soil types along the slope exhibited different morphological characteristics (Jankowski et al., 2018) and varied in their chemistry (Tab. 1), reflected in their soil structure. Changes in the soil structure of the A-horizons were also influenced by human activity in the form of different land use or soil management practices. In A-horizons, the most invasive interventions were also observed (Phaeozem – forest; Cambisol – grass strips; Chernozem – intensive tillage system) compared to deeper located soil horizons, where the soil structure showed signs of higher stability (Tab. 2). Phaeozems were generally like Chernozems and Kastanozems in that they were fertile soils (WRB, 2015). The Phaeozem was used as forest soil, so the combination of minimal interventions in the soil environment and optimal pedogenic properties gave a good base for a favorable state of the soil structure, as confirmed by the results of this study (Fig. 2, 3). Cambisols with often blocky structure (Jankowski et al., 2018) were represented by young soils with properties significantly dependent on the conditions and factors of the soil-forming process. In the case of this study, the Cambisol within the soil transect was used as a vineyard with intensive weed control by intensive soil tillage/loosening for almost 30 years, which intensified mainly water erosion.

For this reason, grassing the inter-rows of vines became a significant elimination measure limiting water erosion 25 years ago, and the result is an improved soil structure (Fig. 2, 3). As published by several authors (Lazcano et al., 2020; López-Vicente et al., 2020), grass strip is an essential anti-erosion measure for improving soil properties, including soil structure in vineyards. In Chernozem, the highest content of WSAmi and lower content, especially of large WSAma, was found in comparison with Phaeozem and Cambisol. Despite the high fertility of Chernozems, the main impact on their final properties (including soil structure) was intensive land use (conventional system based on intensive tillage and fertilization including annual plowing with a plow to a depth of 25 cm). The study of Zaujec & Šimanský (2008) also showed that the structure of intensively used Chernozems as arable soils for food production significantly declined. In the case of this study, the structure of Chernozems was declined by intensive soil management practices, as declared by the results – a significant decrease in MWDw on the one hand and, on the other hand, an increase in the vulnerability of the soil structure (Fig. 3).

Additional impact on soil structure and aggregate stability also includes slope reduction. According to e.g. Poesen and Hook (1997) and Carroll et al. (2000), changes in slope inclination have a crucial influence on soil erosion, which is an important phenomenon causing significant loss of organic matter and finer soil particles, which are treated as one of the main factors influencing soil structure. Research results presented by Lyle and Tomlinson (1999) indicate an increase in soil compaction and a reduction of soil porosity. Soil aggregates can become less stable on steeper slopes, which has a negative impact on soil porosity and other physical soil properties. The highest stability of water-stable aggregates found in Cambisol may result from a relatively small slope inclination and minor mechanical, human intervention in land cultivation (strip grass between the vine). The highest situated Luvic Chernic Phaeozem (Loamic) was characterized by the relative stability of water-stable aggregates resulting mainly from the high content of silt, clay, soil organic carbon (Tab. 1), and the type of land use (deciduous forest – Fig. 1). However, in view of the high slope inclination, this soil did not achieve the greatest stability of aggregates compared to Cambisol, which is located in the lower parts of the slope. In Cambisol, the high content of the finest particle-size fractions (Tab. 1) was also observed, which could also affect the soil structure. The greatest stability of soil structure is expected in flat areas, however, due to agricultural use, the greatest stability of aggregates is not observed in Chernozem.

Effect of soil properties on soil aggregation along the soil types

Many studies indicate a close relationship between soil organic matter (SOM) and soil structure (Bronick & Lal, 2005; Šimanský et al., 2021; Halder et al., 2024); however, this was not confirmed in this study. Soil organic carbon ranged from 9 to 49 g kg^{-1} (Jankowski et al., 2018), resulting in no significant correlations with soil structure compared to other soil properties (Tab. 3). The reason for this could be individual forms of SOM. Itami & Kyuma (1995) reported that anions of organic compounds such as fulvates, citrates, oxalates or acetates increase clay dispersion. In addition, SOC is influenced by a range of biotic and abiotic factors, including climate, topography, vegetation, soil properties, and soil management practices, which often interact with and regulate C inputs and losses from the soil. In this study, a higher C/N ratio positively affected the increase of small WSAma (1-0.5 mm) and WSAmi. Soil aggregates are formed hierarchically (Oades & Waters, 1991), or smaller aggregates are formed within large aggregates, with the decomposition of SOM within macroaggregates being decisive (Six et al., 2004). The results of this study indicate that, in the studied A-horizons of soils, due to SOC immobilization in primary soil organic matter was increased contents of smaller WSAma 1-0.25 mm and WSAmi which are more stable, as confirmed by several authors (Oades & Waters, 1991). A narrower C/N ratio, resulting from a higher nitrogen content in the primary organic matter, caused more intense decomposition, which in turn promoted aggregation, primarily the merging of microaggregates and smaller macroaggregates into larger clusters of macroaggregates. The higher content of water-stable aggregates (WSAs) > 5 mm and 5-3 mm was a result of the narrower C/N ratio (Tab. 3). As the primary organic matter decomposes more intensively, larger aggregates are formed. High carbonate content reduces the vulnerability of soil structure and increases MWDw (Tab. 3). Carbonates are sources of Ca and Mg, which contribute to forming soil structure through cationic bridges (Bronick & Lal, 2005). They are more effective in soils with a finer textures (Le Bissonnais, 1996), which partially confirmed the results of this study. Silt content was positively correlated with large WSAma (5-3 mm) and negatively with small WSAma (1-0.5 mm) and WSAmi.

Higher silt content improved the water stability of the aggregates by increasing the MWDw and reducing the Kv values. Higher clay content had a positive effect on MWDd (Tab. 3).

Conclusions

Favorable soil structure and its vulnerability were influenced from topography, soil material variability, land use, and intensity of soil management practices. The most vital stability of water-stable aggregates was found in Cambisol, followed by Phaeozem and Chernozem. Likewise, the vulnerability of soil structure was the lowest in Cambisol, and the highest in Chernozem. Soil organic carbon content did not have a significant effect on soil structure. However, the mineralization of soil organic matter led to increased aggregation, particularly WSAma in the 3-5 mm and > 5 mm size fractions. Conversely, the immobilization of soil organic carbon in soil organic matter mainly supported the increase of smaller WSAma (1-0.25 mm) and WSAmi. The increase in large WSAma (> 3 mm) was link to higher carbonate and silt contents in the soils. This topic requires more detailed research to precisely assess the dominant factor in shaping the soil structure in areas with steep slopes. This issue is extremely important due to the increased risk of water erosion and potential soil degradation in such areas. Additionally, it may allow for the development of techniques to prevent the destruction of soil structures on steep slopes regardless of land use type.

Editors‘ note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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