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ORIGINAL PAPER

STABILITY OF SOIL AGGREGATES IN LOAMY SOILS OF SLOVAKIA*

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Abstract

Stability of soil aggregates is affected by dozens different factors and their individual effects are hardly discernable. For this reason, we investigated the structure of the top layer (to a depth 0.2 m) of loamy soils (Haplic Fluvisol, Mollic Fluvisol and Calcaric Chernozem), at three sites (Šulekovo, Trakovice and Bučany) in the north-western part of the Danube Lowlands (Slovakia) in order to: (1) evaluate the differences in soil organic matter (SOM), texture, water-stable aggregates (WSA) and content of SOM in WSA; (2) determine the relationships between SOM, texture and WSA; and (3) identify the threshold limits for soil organic carbon (SOC) and the particle-size distributions for stabilization of water-stable macro-aggregates (WSA_{ma}). We found significant effects of a soil type on both SOM and WSA as well as on the content of SOM in WSA. When all loamy soils were assessed together, positive significant correlations were observed between size fractions of WSA_{ma} >2 mm and the content of SOC and hot-water soluble carbon (C_{HWD}). The content of WSA_{ma} 1-0.25 mm and water-stable micro-aggregates (WSA_{mi}) correlated negatively with SOC and C_{HWD}. The quality of SOM was more important than its quantity for the stabilization of WSA_{ma} at size fractions 1-0.25 mm and WSA_{mi}. The content of clay improved the aggregation in size fractions of WSA_{ma} >2 mm in the investigated top layer of loamy soils. The maximum WSA_{ma} content occurred where the ratio of organic carbon content in WSA_{ma} to that in soil was ~1.0. The threshold limits for clay and silt content for the formation of WSA_{ma} were ~20% and equal to 43%, respectively.

Keywords: soil organic matter, water-stable aggregates, threshold limit, Chernozems, Fluvisols.

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INTRODUCTION

Soil structure is a key factor in the functioning of soil and its ability to promote crop growth, as an optimal soil structure supports plants in terms of sufficient water supply, aeration and release of available nutrients, and therefore is the key factor of soil quality (Roger-Estrade et al. 2010, Garbout et al. 2013). Soil aggregates are the basic units of soil structure (Young, Warkentin 1975) that result from the aggregation of primary soil particles into compound particles, or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness (Millar et al. 1962).

There are several known mechanisms of aggregation, which have been reported by Amézketa (1999) and by Bronick, Lal (2005), and several authors (Grosbellet et al. 2011, Zhang et al. 2012, Chinchalikar et al. 2012, Li, Fan 2014) have presented formation of soil aggregates as a function of physical forces. One of the most important attributes of aggregates is their stability (Six et al. 2004), which is used as an indicator of such soil responses as susceptibility to runoff and erosion. Amézketa (1999) divided factors affecting aggregate stability into two main groups: (1) internal and (2) external factors. Internal factors affecting aggregate stability comprise the content and concentration of polyvalent cations (Paradelo et al. 2013) and particle-size distribution (Attou et al. 1998, Leinweber et al. 1999), soil organic matter – SOM (Rabbi et al. 2015). External factors include wet-dry cycles (Singer et al. 1992), freeze-thaw cycles (Li, Fan 2014), and biological factors such as soil micro-organisms (Tisdall, Oades 1982), soil macro-organisms e.g. earthworms (Jegou et al. 2001), plant roots (Kurakov, Kharin 2012) and soil management practices (Balashov, Buchkina 2011). Moreover, aggregate stability depends on a soil layer or horizon in an individual soil type. For example, in Alfisols, aggregate stability has been shown to depend on soil SOM (Oades, Waters 1991). The main factors responsible for aggregation in Vertisols are clay-sized fractions (Leinweber et al. 1999), and in Oxisols these are the Al^{3+} and Fe^{3+} oxides as well as SOM (Rabbi et al. 2015) that are of primary importance.

In this context, we hypothesized that in such soils as Chernozems or Fluvisols, which are the most fertile soils in Slovakia (Bielek et al. 1998), soil aggregates can be stabilized by SOM and mineral particles in the top layer. We therefore attempted to evaluate the structure of loamy soils of Slovakia by addressing the following particular objectives: (1) evaluating the differences in SOM, texture, and water-stable aggregates (WSA), and in the WSA content of SOM; (2) determining the relationships between SOM, texture and individual size fractions of WSA; and (3) determining the threshold limits for SOM and the particle-size distributions that are significant for formation and stabilization of water-stable macro-aggregates.

MATERIAL AND METHODS

Study sites

The study sites are located in the north-western part of the Danube Lowlands, between the towns of Hlohovec and Trnava, in the western part of Slovakia (Figure 1). The geological substrates of the investigated region are

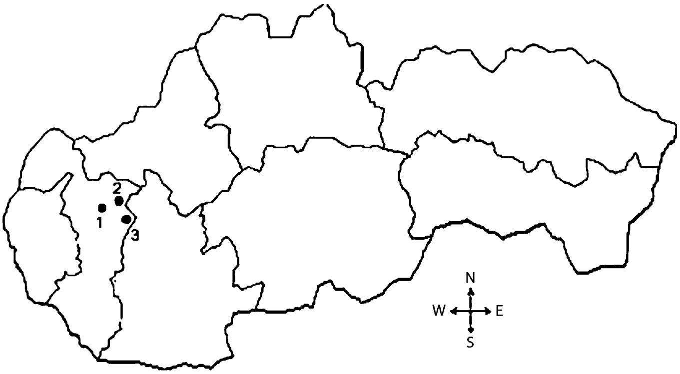

Fig. 1. Selected sites in Slovakia:
1: – Bučany, 2: – Trakovice, 3: – Šulekovo

Neogene clays, sands and gravels, which are mostly covered with loess and loess-loam. Fluvial sediments are found along the rivers Váh and Dudváh. One site is situated in a flat area on the Váh River near the village of Šulekovo (48° 26′ 3.72″ N, 17° 46′ 7.88″ E), another one is located near a flat area on the Dudváh River in the vicinity of the village of Trakovice (48° 26′ 21″ N, 17° 42′ 31″ E) and the last one lies on some gentle slopes near the village of Bučany (48° 25′ 22.3″ N, 17° 42′ 8.6″ E). The sites are characterized by temperate climate, with an average annual temp. of 9.8°C and average annual precipitation of 580 mm. In 2011, in terms of temperature and precipitation these sites were characterized as normal and dry, respectively, in line with the classification of Kožnarová, Klabzuba (2002). In the spring of 2011, soil surveys were conducted in the selected sites. The soil in a field near Šulekovo was classified as loamy Haplic Fluvisol, in Trakovice as loamy Mollic Fluvisol, and in Bučany as loamy Calcaric Chernozem (WRB 2006). The major characteristics of the top layer of soil at each site (0-0.2 m) are shown in Table 1.

At all the sites, the soils had been cultivated for over 100 years. In 2011, sugar beet (*Beta vulgaris* L. *var. altissima*) was grown in all the fields, always following spring barley (*Hordeum sativum* L.). In autumn 2010, the soil was ploughed to the depth of 0.25 m and farmyard manure was applied to Haplic Fluvisol in a dose of 40 t ha^{-1}. In the first decade of May, sugar beet was sown in all the fields.

Table 1

Soil characteristics (means) in the top layer 0-0.2 m (Šimanský, Kováčik 2014)

Soil types	pH	CEC	$CaCO_3$	Sand > 0.05 mm	Silt 0.05 - 0.001 mm	Clay <0.001 mm
		(cmol kg^{-1})	(%)			
Calcaric Chernozem	7.8±0.04	18.7±0.12	9.28±1.04	43±3.95	47±3.17	10±1.48
Haplic Fluvisol	7.6±0.06	17.8±0.16	2.12±0.27	38±6.13	40±2.85	17±3.94
Mollic Fluvisol	7.8±0.03	17.2±0.20	11.6±0.94	47±3.69	38±4.29	14±1.83

pH – soil pH_{H_2O}, CEC – cation exchange capacity, $CaCO_3$ – content of carbonates, ± – standard deviation.

Soil sampling and analytical methods

At each site, four places (size of area: 1 x 1 m; and apart from each: 20 m) were chosen randomly for repeated soil sampling from these locations. The soil samples were taken from a depth of 0-0.2 m during the sugar beet growing season in 2011 (25 May, 18 June, 15 July, 14 August, 15 September, 16 October). On each sampling date, the four soil samples were mixed to produce an average representative sample from each study site. Any roots and large pieces of plant litter were removed. The collected soil samples were transported to a laboratory and large clods were gently broken up along natural fracture lines, followed by air-drying at laboratory temperature.

The soil organic carbon (SOC) content was assessed by the Tyurin method of wet oxidation. The mixture used was 0.07 M H_2SO_4 and $K_2Cr_2O_7$ (temp. of heating 150°C during 20 min), with titration using 0.01 M Mohr's salt as described by Dziadowiec, Gonet (1999). The labile carbon content (C_L) was extracted from 1 g soil samples by shaking them in 50 mL of 0.005 M $KMnO_4$ for two hours. After centrifugation, the C_L was determined by oxidation of 0.07 M H_2SO_4 and $K_2Cr_2O_7$ with titration using 0.05 M Mohr's salt (Łoginow et al. 1987). Hot-water soluble carbon (C_{HWD}) was extracted from 10 g soil samples by shaking them in 100 mL of distilled water at 80°C for 16 hours. After drying the extract, the C_{HWD} was determined using wet oxidation according to the Tyurin method (Kőrschens 2002). The fractional compositions of humic substances – humic (HA) and fulvic (FA) acids – were determined using the Tyurin method as modified by Ponomareva-Plotnikova (Dziadowiec, Gonet 1999). This was followed by calculating the C_{HA}:C_{FA} ratio as the quality parameter of SOM. The particle-size distribution was determined after dissolution of $CaCO_3$ with 2 M HCl and decomposition of the organic matter with 6% H_2O_2. After repeated washing, the samples were dispersed using $Na(PO_3)_6$. Silt, sand and clay fractions were determined according to the pipette method as described by Fiala et al. (1999). The size classes of WSA were determined using the Baksheev method (Vadjunina, Korchagina 1986). Thus, the soil sample was first overflowed with distilled water (water level 1 cm above aggregates). After two hours, the sample was transferred to the top sieve (>5 mm) in a cylindrical container (Baksheev device), which was filled with distilled water. The cylinder was hermetically sealed and the sample was sieved for 12 minutes. The size fractions of water stable aggregates (WSA) were the following: >5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25 mm (macro-aggregates, WSA_{ma}) and <0.25 mm (micro-aggregates, WSA_{mi}). The remaining material except for micro-aggregates was quantified in each sieve. The micro-aggregate fraction calculated as the difference between the total weight of the soil sample and the sums of macro-aggregates. In each size fraction of the WSA, we measured soil organic carbon (SOC in WSA) as mentioned above (Dziadowiec, Gonet 1999).

Statistical analysis

Before performing the statistical analysis, the data were checked for normal distribution. The statistical analysis was performed using the Statgraphics Centurion XV.I programme (Statpoint Technologies, Inc., USA). A one-way ANOVA model was used for comparisons of investigated parameters in the 0-0.2 m layer between soil types at $P \leq 0.05$, followed by the LSD (least significant difference) test for separation of the means. The interrelations between SOM, texture and WSA fractions were determined through a correlation matrix. Pearson *r* coefficients were calculated to test the one-to-one relationships between variables (SOC in WSA/SOC in soil ratios and contents of WSA_{ma}, particle-size distribution and content of WSA_{ma}).

RESULTS AND DISCUSSION

Soil characteristics in study sites

The different soil types showed significantly different SOM content in top layers (Table 2). In comparison to Calcaric Chernozem, the values of SOC, C_L and C_{HWD} were higher in Haplic Fluvisol by 78%, 47%, and 29%, and in Mollic Fluvisol by 61%, 5%, and 37%, respectively. These differences are mainly due to different soil-forming processes (Duchaufour 1982) but can also be affected by soil management (Slowinska-Jurkiewicz et al. 2013). For example, in the studied Calcaric Chernozem, the content of SOC in the top layer was influenced by inappropriate soil management practices (ploughing the soil on the slope, which is overall an unsuitable choice of a field for growing sugar beet). In Calcaric Chernozem (1.44±0.18), the average values of C_{HA}:C_{FA} ratio (SOM quality parameter) were higher than in Haplic (1.07±0.03) and Mollic Fluvisols (1.05±0.08). Generally, the Chernozems are among the best and the most fertile soil types in Slovakia owing to their optimal chemical and physical properties (Bielek et al. 1998). All the mentioned soils were tilled using a conventional system (ploughed to the depth of 0.25 m), and several authors (Dou, Hons 2006, Šimanský et al. 2008) have

Table 2

Parameters of soil organic mater (means) in investigated soil types (0-0.2 m)

Soil types	SOC (g kg^{-1})	CL (mg kg^{-1})	CHWD (mg kg^{-1})	CHA:CFA
Calcaric Chernozem	11.9±0.8^{a}	1686±130^{a}	480±37^{a}	1.44±0.18^{b}
Haplic Fluvisol	21.2±1.1^{b}	2470±232$_{b}$	618±31^{b}	1.07±0.03^{a}
Mollic Fluvisol	19.2±1.2^{b}	1777±134$_{a}$	655±42^{b}	1.05±0.08^{a}

SOC – soil organic carbon, CL – labile carbon, CHWD – hot water soluble carbon,
CHA:CFA – carbon of humic acids and fulvic acids ratio, ± – standard deviation;
Different letters between lines (*a*, *b*, *c*) indicate significant differences between top layers of soil types at $P \leq 0.05$ according to LSD multiple-range test.

pointed out that the quality of SOM in cultivated soils is better than in no -till systems as humus has a higher portion of condensed structure units, which increases the C_{HA}:C_{FA} ratio. These differences can be connected with soil management practices such as fertilization (Szombathová et al. 2001, Polláková et al. 2016) and incorporation of crop residues to soil (Šimanský et al. 2008).

Water-stable aggregates and carbon in water-stable aggregates

There were significant differences in the top layers between the soil types regarding the WSA content (Table 3), which coincides with similar results published by several authors (Gama-Rodrigues et al. 2010, Šimanský, Bajčan 2014). During the sugar beet growing season, we observed the highest average content of WSA_{ma} in Mollic Fluvisol while the lowest content was in Calcaric Chernozem. The content of WSA_{ma} in size classes from 0.5 to 3 mm is important from the agronomic point of view, and their average

Table 3

Content of water-stable aggregates and content of organic carbon in water-stable aggregates (means) in investiged soil types (0-0.2 m)

Soil types	>5	5-3	3-2	2-1	1-0.5	0.5-0.25	<0.25
Content of water-stable aggregates (%)							
Calcaric Chernozem	1.81^{a}	1.73^{a}	4.47^{a}	13.14^{a}	23.80^{b}	19.48^{b}	31.84^{b}
Haplic Fluvisol	16.65^{b}	13.28^{b}	14.31^{b}	15.61^{a}	13.52^{a}	10.99^{a}	13.00^{a}
Mollic Fluvisol	17.86^{b}	16.55^{b}	17.82^{c}	18.22^{a}	13.62^{a}	10.41^{a}	8.55^{a}
Content of organic carbon in water-stable aggregates (g kg^{-1})							
Calcaric Chernozem	11.0^{a}	13.0^{a}	12.9^{a}	13.3^{a}	12.3^{a}	11.3^{a}	9.30^{a}
Haplic Fluvisol	22.3^{b}	21.8^{c}	21.6^{c}	20.9^{b}	21.2^{b}	19.6^{c}	17.5^{c}
Mollic Fluvisol	19.3^{b}	19.6^{b}	19.1^{b}	20.8^{b}	19.6^{b}	16.2^{b}	14.5^{b}

Different letters between lines (*a*, *b*, *c*) indicate significant differences between top layers of soil types at $P \leq 0.05$ according to LSD multiple-range test.

values were higher by 17% and 5% in Mollic Fluvisol and Haplic Fluvisol, respectively, than in Calcaric Chernozem. In terms of the content of WSA_{ma} > 5 mm, the soils were arranged in the following decreasing order: Mollic Fluvisol > Haplic Fluvisol > Calcaric Chernozem.

In all the soil types, the content of SOC in WSA_{mi} to the depth 0.2 m was lower than WSA_{ma}. The lowest content of SOC in WSA_{mi} was in Calcaric Chernozem and the highest content was found in Haplic Fluvisol. The same trend was observed in the content of SOC in the soils (Table 2). The content of SOC in soil depends on particle-size distribution. NEUFELDT et al. (2002) reported a positive relationship between clay and the SOC content. The content of SOC in WSA can be also affected by particle-size distribution. For example, if WSA contains clay or silt-size minerals, these will retain more carbon inside the aggregates (SIX et al. 2004). On the other hand, if aggregates show a higher sand content, there will be less C retained. The extent of saturation capacity of WSA by SOM is also dependent on the content of clay minerals, their phyllosilicate composition and intra-aggregate pores, which are involved in adsorption and stabilization of SOM (WISEMANN, PÜTTMANN 2006, KÖGEL-KNABNER et al. 2008). The one-way ANOVA showed significant differences between the top layers of the analyzed soil types in the re-distribution of SOC among individual size fractions of WSA_{ma} (Table 3). The average content of SOC in WSA_{ma} in the top layer of the different soil types was (in decreasing order): Haplic Fluvisol (2.12±0.10%) > Mollic Fluvisol (1.91.±0.15%) > Calcaric Chernozem (1.23±0.09%). The highest SOC content in Haplic Fluvisol was found in the size fraction WSA_{ma} > 5 mm (22.3 g kg^{-1}) while in both Calcaric Chernozem (13.3 g kg^{-1}) and Mollic Fluvisol (20.8 g kg^{-1}) it was in the size WSA_{ma} 2-1 mm fraction.

Relationships between soil parameters and size fractions of water-stable aggregates

The correlation coefficients for soil parameters and size fractions of WSA are summarized in Table 4. When all the top layers of loamy soils (to the depth 0.2 m) were assessed together, positive significant correlations were observed between size fractions of WSA_{ma} >2 mm (sum of >5 mm, 5-3 mm and 3-2 mm) and contents of SOC and C_{HWD}. Macro-aggregate stability is known to be positively correlated with SOC (BLAVET et al. 2009) as a result of strong linkage between the colloidal fractions of soils (KIRKBY, MORGAN 2005). However, SOC and C_{HWD} in soil were negatively correlated with smaller fractions of WSA_{ma} (1-0.25 mm) and with the content of WSA_{mi}. These results showed that stabilization of WSA_{ma}, often promoted by the growth of roots and fungal hyphae, i.e. intra-macroaggregate particulate organic matter, may be an important agent facilitating the binding of micro-aggregates into macro-aggregates (DABEK-SZRENIAWSKA, BALASHOV 2007). Applying farmyard manure (ZHAO et al. 2008) or ploughing plant residues into soil (CASSEL et al. 1995) are associated with the higher stabilization of greater fractions of

Table 4

Correlations between soil organic matter parameters, particle-size distribution and size fractions of water-stable aggregates (all top layers of loamy soils assessed together)

Size fractions of water-stable aggregates (mm)	SOC	CL	CHWD	CHA:CFA	Sand	Silt	Clay
>5	0.604^{**}	n.s.	0.643^{**}	-0.565^{*}	n.s.	n.s.	0.610^{**}
5-3	0.821^{***}	n.s.	0.848^{***}	-0.748^{***}	n.s.	n.s.	0.721^{***}
3-2	0.842^{***}	n.s.	0.876^{***}	-0.777^{***}	n.s.	n.s.	0.575^{*}
2-1	n.s.	n.s.	n.s.	n.s.	n.s.	-0.488^{*}	n.s.
1-0.5	-0.519^{*}	n.s.	-0.509^{*}	0.554^{*}	n.s.	n.s.	n.s.
0.5-0.25	-0.578^{*}	n.s.	-0.598^{*}	0.550^{*}	n.s.	n.s.	-0.506^{*}
<0.25	-0.728^{***}	n.s.	-0.809^{***}	0.710^{***}	n.s.	n.s.	-0.540^{*}

SOC – organic carbon, CL – labile carbon, CHWD – hot-water soluble carbon, CHA:CFA – carbon of humic acids and fulvic acids ratio, n.s. – non-significant, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

WSA_{ma}. In all the top layers of the soil types, plant residues of spring barley were ploughed in, but farmyard manure was applied only to Haplic Fluvisol.

A conclusion can be drawn from our results that when all the top layers of loamy soils were assessed together, the stabilization mechanism of smaller size fractions (1-0.25 mm) of WSA_{ma} as well as WSA_{mi} relied not on the quantity of SOM, but on its quality (C_{HA}:C_{FA} ratio), which was shown by relevant positive correlations (Table 4). On the other hand, a negative correlation was found between the >2 mm size fractions of WSA_{ma} and C_{HA}:C_{FA} ratios. This means that the stabilization of larger-sized fractions of WSA_{ma} in all the studied top layers of soil types should depend on other factors, for example, positive effects of carbonate content (Vaezi et al. 2008) or polyvalent cations and clay particles (Shein et al. 2013).

There was a strong linear relationship between the SOC in WSA_{ma} and WSA_{ma} contents only when all the top layers of loamy soils were assessed together; these results did not enable us to distinguish the maximum formation of WSA_{ma} by SOC in the soils, therefore we did not give any threshold limit for SOC in WSA_{ma}. No linear relationship was observed between SOC in WSA_{ma} to SOC in soil ratios and WSA_{ma} contents (Figure 2*a*). Our data also showed that the maximum WSA_{ma} content in the soils was observed if the ratio of SOC content in WSA_{ma} to those in bulk soil was ~ 1; any further increase in the ratios did not result in further WSA_{ma} accumulation (Figure 3*a*). These results supported our data showing that there were maximum thresholds of WSA_{ma} saturation capacity by total SOC involved in the water-stable aggregation. According to several studies (Six et al. 2004, Wiseman, Puttmann 2006), the extent of saturation capacity is dependent on the amount of clay particles and amount of intra-aggregate pores, which are involved in adsorption and stabilization of SOM.

Our results showed that the clay content was positively correlated with

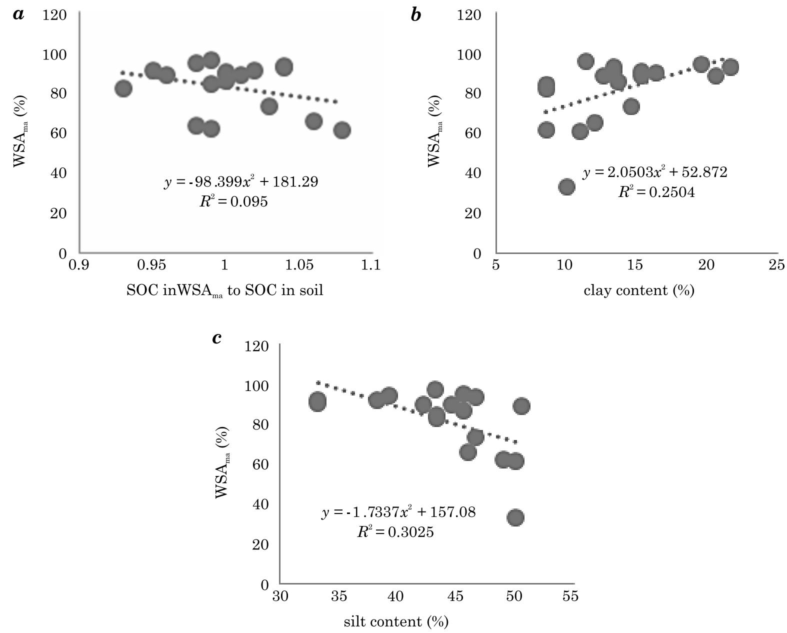

Fig. 2. Relationship (linear) between (*a*) the ratio of SOC in WSA$_{ma}$ to SOC in soil and amount of WSA$_{ma}$, (*b*) the clay and amount of WSA$_{ma}$ and, (*c*) the silt and amount of WSA$_{ma}$

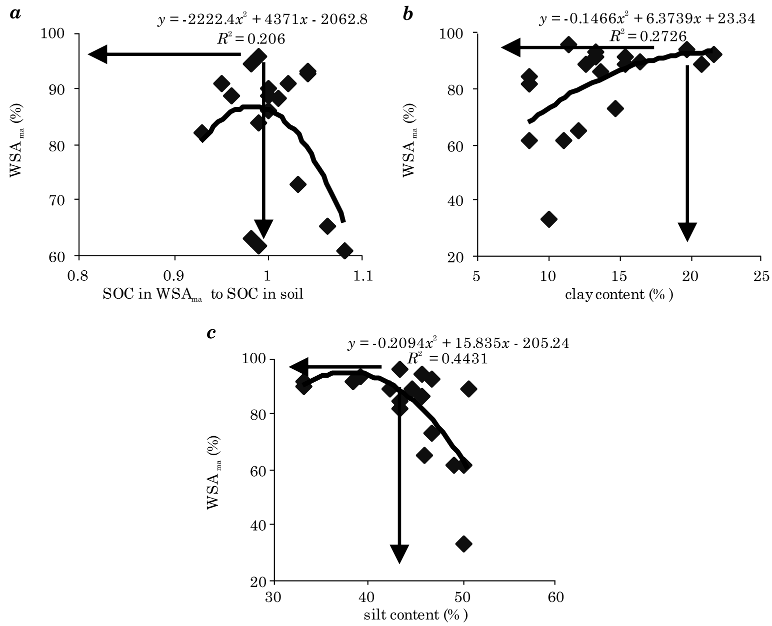

Fig. 3. Relationship (polynomial) between (*a*) the ratio of SOC in WSA$_{ma}$ to SOC in soil and amount of WSA$_{ma}$, (*b*) the clay and amount of WSA$_{ma}$ and, (*c*) the silt and amount of WSA$_{ma}$

size fractions of WSA_{ma} >2 mm; however, the content of smaller size fractions of WSA_{ma} (1-0.25 mm) as well as that of WSA_{mi} were negatively correlated with the clay content. The silt content had a significant negative relationship with WSA_{ma} 2-1 mm. The content of sand was not correlated with WSA. Significant positive linear relationships were determined between clay as well as silt contents and WSA_{ma} (Figure 2*b*, *c*). According to the results of the polynomial regression analysis, a threshold value of clay content of ~ 20% corresponded to the maximum content of WSA_{ma}, with an increase in the clay content resulting in a lower WSA_{ma} content (Figure 3*b*). When all the top layers of soils were assessed together, the threshold value of the silt content equalled 43% at the maximum content of WSA_{ma} (Figure 3*c*).

CONCLUSION

Our study demonstrated that when all the selected top layers of loamy soils of Slovakia were assessed together, the process of stabilization of smaller fractions of WSA_{ma} 1-0.25 mm as well as WSA_{mi} depended on SOM quality rather than on the quantity of SOM, and that the content of clay improved the aggregation in size fractions of WSA_{ma} > 2 mm. The content of WSA_{ma} had a maximum value when the ratio of organic carbon content in WSA_{ma} to that in soil was ~1.0. The results underline the importance of soil aggregation and more specifically the interactions of SOM and aggregate dynamics in controlling C-sequestration in the studied soils. The threshold limits for the clay and silt content for the formation of water-stable macro -aggregates were ~20% and 43%, respectively. A further increase resulted in a lower content of WSA_{ma}.

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