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Original Paper

Stabilization of water-stable aggregates under forest and agricultural soils

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Stability of soil aggregates was studied in forest and agricultural soils classified as: Cambisols, Luvisols and Chernozems, where we evaluated: (i) the differences in water-stable aggregates (WSA) with dependence on soil types and land use, (ii) the relationships between soil organic carbon (SOC), labile carbon (CL), soil texture and individual size classes of WSA, and (iii) the relationships between SOC, CL and soil textural fractions within WSA. When all soils were evaluated together, our results showed statistically significant linear relationships between water-stable micro-aggregates (WSA$_{mi}$), water-stable macro-aggregates (WSA$_{ma}$) >1 mm and content of SOC. The content of SOC in WSA$_{ma}$ have been in positive linear dependence with individual size classes of WSA$_{ma}$ 1–5 mm. Higher humus quality positively influenced the stability of WSA$_{ma}$ >5 mm. In forest soils we determined higher contents of WSA$_{ma}$ than WSA$_{mi}$ in comparison to agricultural soils. A higher content of CL in WSA$_{mi}$ had a positive effect on stabilization of WSA$_{mi}$ in forest soils. In agricultural soils, the fraction of coarse sand was more represented in WSA$_{ma}$ >1 mm. In forest soils, higher contents of fine sand and coarse silt resulted in higher contents of WSA$_{ma}$ 0.25^{-3} mm.

Keywords: soil organic matter; soil texture; aggregate stability; forest soil

1 Introduction

Formation of soil aggregates is a function of physical forming forces (Grosbellet et al., 2011; Li and Fan, 2014; Hu et al., 2015). There are several ionic forces involved in formation of floccules, domains, and aggregates. Principal among these are inter and intramolecular forces, electrostatic and gravitational forces (Lal and Shukla, 2004). There are two internal forces that dominate soil particles interaction in aqueous solution: the electrostatic repulsive force and the van der Waals attractive force (Zhang et al., 2012; Chinchalikar et al., 2012). The mechanism of aggregation involves exogenous driving forces and the endogenous interactive forces arising from the soil-water interaction. Consequently, the specific arrangement of soil particles as observed in the field is dictated by the nature of exogenous and endogenous forces involved. Formation and stability of natural soil aggregates are affected by dozens of different factors and their individual effects are hardly distinguishable (Amézketa, 1999; Józefaciuk and Czachor, 2014). Aggregate stability is affected by soil intrinsic factors as electrolyte concentration, types of exchangeable cations, clay mineralogy, contents of carbonates, soil organic matter, Fe and Al oxides (Amézketa, 1999). All depends on climate, soil-forming processes, biological factors and soil management practices (Tisdall and Oades, 1982; Šimanský, 2011; Balashov and Buchkina, 2011).

Since there are differences in formation and stabilization of soil aggregates with dependence on soil type (Šimanský and Bajčan, 2014) and land use, the purpose of this study was to make clear which components stabilize the individual size fractions of water-stable aggregates in forest and agricultural soils. In our study, water-stable aggregates (WSA) of different size classes were separated both from three different soil types (Cambisol, Luvisol, Chernozem) and different land use (forest soil, agricultural soil). We studied: (i) the differences in WSA with dependence on soil types and land use, (ii) the relationships between soil organic carbon, labile carbon, particle-size distribution and individual size classes of WSA, and (iii) the relationships between soil organic carbon, labile carbon, and particle-size distribution within WSA.

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2 Material and methods

2.1 Study sites

This study was done using soil samples collected from three localities. First locality is situated near Brno (Czech Republic) and is called Soběšice (49° 14′ 52.3" N, 16° 36′ 33.9 "E). The parent material of the investigated region are granodiorites. The mean annual temperature is 8 °C and the mean annual precipitation is 530 mm. Second and third localities are situated in the western part of Slovakia: Báb (48° 18′ 5.50" N, 17° 53′ 56.59" E) is located near the town of Nitra; and Vieska nad Žitavou (48° 19′ 4.88" N, 18° 22′ 3.17" E) is situated near the town of Zlaté Moravce. The parent material in Báb locality is calcareous loess, the mean temperature 10.2 °C and the total mean annual precipitation is 539 mm (Szombathová and Zaujec, 2001). The soils in Vieska nad Žitavou were developed from Neogene clays, sands and rubble sands which are almost all covered by wind-deposited loess. The mean temperature in the area is 10.6 °C and the total mean annual precipitation is 541 mm (Polláková, 2013).

At each locality two soil pits were dug: one on forest soils and the second one on agricultural soils. In total, 6 soil pits in 3 locations were prepared. On the whole-profile soil morphology the soils were classified according to the World Reference Base for Soil Resources (WRB, 2015) as a Dystric Cambisol, a Haplic Luvisol and a Cambic Chernozem at the localities Soběšice, Vieska nad Žitavou and Báb, respectively. Studied soils in A horizons had acid, neutral and weakly acid pH in Soběšice, Vieska nad Žitavou and Báb, respectively. All soils are loamy, with average content of clay 22.2%, 27.5% and 26.0%, in Soběšice, Vieska nad Žitavou and Báb, respectively. In forest soil, the content of soil organic carbon in A horizons was: 4.15% in Dystric Cambisol, 4.66% in Haplic Luvisol and 4.51% in Cambic Chernozem. In arable soils the content of soil organic carbon was less than half compared to forest soil (2.21% in Dystric Cambisol, 1.27% in Haplic Luvisol and 1.93% in Cambic Chernozem). More dates on soil characteristics of studied soils is published in Polláková et al. (2017).

2.2 Description of study localities

Soběšice: (1) Forest soil: 101 years old mixed forest stand *Quercus petraea* /Mattuschka/ Liebl. 69%, *Carpinus betulus* L. 22%, and *Pinus sylvestris* L. 9%. (2) Agricultural soil: extensive meadow dominated by *Poa pratensis* L. and *Dactylis glomerata* L.

Báb: (3) Forest soil: more than 200 years old deciduous forest with predominance of *Quercus robur*, L. and *Carpinus betulus*, L. (4) Agricultural soil: arable land, yearly ploughed for minimally 100 years. Maize was grown during sampling on the field; forecrop had been winter wheat.

Vieska nad Žitavou: (5) Forest soil: more than 70 years old monoculture growth of *Thuja occidentalis* L. (6) Agricultural soil: arable land, yearly ploughed for minimally 100 years. Maize was grown on the field at the time of sampling; the forecrop had been sunflower.

2.3 Soil sampling and analyses

Soil samples were taken from topsoil (to 0.3 m). Roots and litter were removed from the samples before mechanical and chemical treatment. Then the samples were air-dried at laboratory temperature and ground. In this study, each soil sample was divided into six particle size fractions by the pipette method (Hrivňáková et al., 2011). The content of soil organic carbon (SOC) was determined using the dichromate-sulfuric acid oxidation by the Tyurin method (Orlov and Grishina, 1981). The fractional compositions of humic substances according to Tyurin in modification of Ponomareva-Plotnikova (Orlov and Grishina, 1981) were determined as well. The extinctions of humic substances and humic acids were measured at 465 and 650 nm by 6400 Spectrophotometer (Jen Way), on the base of which the colour quotients of humic substances ($Q^{4/6}_{HS}$) and humic acids ($Q^{4/6}_{HA}$) were calculated.

Soil samples for aggregates determination were carefully collected using a spade. By their mixing we obtained an average representative sample from each of six study sites. Roots and large pieces of litter were removed. Samples were transported to the laboratory and large clods were gently broken up along natural fracture lines. After air-drying at laboratory temperature we obtained undisturbed soil samples. To determine water-stable aggregates (WSA) we used the AS 200 device Retsch®. Wet sieving was done by four sieves with mesh diameter of 5, 3, 1 and 0.25 mm. After the sieving process, the size classes were transferred from the individual sieves to filter paper and dried in a drying cabinet at 45 °C. The material retained was quantified in each sieve except micro-aggregates, for which the content was calculated as the difference between total weight of the soil sample and the sums of the macro-aggregates. The size classes of water-stable aggregates >0.25mm are macro-aggregates (WSA_{ma}) and <0.25 mm are micro-aggregates (WSA_{mi}). Mechanical and chemical analyses were carried out in all size classes of WSA. Particle-size distribution was analysed by pipette method (Hrivňáková et al., 2011). Total organic carbon in WSA (SOC in WSA) was determined by the Tyurin method, labile carbon by the Loginov method (Loginow et al., 1987).

2.4 Statistical analyses

The statistical analysis was performed using the Statgraphics Centurion XV.I programme (Statpoint Technologies, Inc., USA). A one-way ANOVA model was used for individual comparisons of different aggregate fractions at $P \leq 0.05$, with separation of the means by the LSD test. Relationships between SOC, CL, particle-size distribution and individual size classes of WSA as well as between SOC and CL and particle-size distribution within WSA were then determined.

3 Results and discussion

3.1 Contents of water-stable aggregates

Land use in individual soil types had statistically significant influence on changes in size classes of WSA$_{ma}$. Mainly in Cambisol in size classes of WSA$_{ma}$ 1–0.25, 3–1 and 5–3 mm as well as in Luvisol in WSA$_{ma}$ 1–0.25 mm the most significant differences were observed (Figure 1). Generally, in all soil types under forest the content of WSA$_{ma}$ >5 mm was higher than in agricultural soils. In opposite, higher content of WSA$_{mi}$ in agricultural than forest soils was observed. Almost five times higher content of WSA$_{ma}$ 5–0.25 mm was observed in Chernozem under forest than arable soil. The similar trend was found in Luvisol. Intensive cultivation disrupts soil aggregates, compacts soil and disturbs plant and animal communities, what contribute to the aggregation and decreasing of soil organic matter (Plante and McGill, 2002). On the other hand, higher contents of macro-aggregates than micro-aggregates were observed in forest soils in comparison to agricultural soils (Khurakov and Kharin, 2012) which corresponded with our findings.

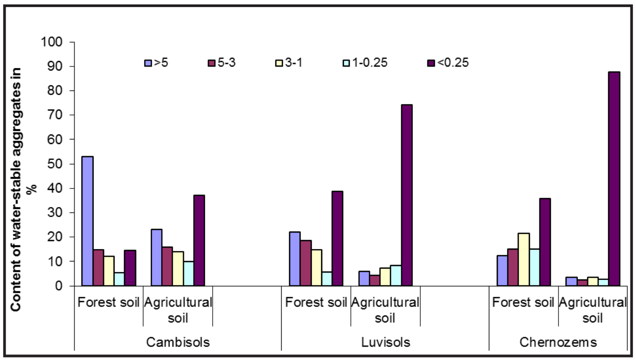

Figure 1 Contents of water stable aggregates in the investigated soils

3.2 Relationships between soil chemical properties, texture composition and individual size classes of water-stable aggregates as well as within water-stable aggregates

The most important internal factor affecting the binding soil mineral particles together is soil organic matter (SOM) (Bronic and Lal, 2005; Krol et al., 2013; Šimanský and Bajčan, 2014) therefore we tested the single relationships between individual size classes of WSA and SOM components. Statistically significant linear relationships between the WSA$_{ma}$ >1 mm (positive) and SOC as well as between the WSA$_{mi}$ (negative) and SOC were observed. Macro-aggregate stability was positively correlated with SOC as a result of a strong bond between the colloidal components of soils (Blavet et al., 2009). We determined positive linear dependences between SOC and CL in WSA$_{ma}$ and individual size classes of WSA$_{ma}$ 5–1 mm and on the other hand, lower content of SOC and CL in WSA$_{mi}$ resulted in higher content of WSA$_{mi}$ when all studied soil types and land uses were evaluated together. Statistically significant linear relationships between content of humic acids (HA) and WSA$_{ma}$ (negative) and WSA$_{mi}$ (positive) were determined which means that WSA$_{mi}$ were stabilised mainly by highly condensed components of organic matter, i.e. humic acids, whereas WSA$_{ma}$ mostly by labile SOM components, which is indicated by highly significantly positive linear dependence between CL in WSA and WSA$_{ma}$ 5–1 mm. With the increased content of fulvic acids (FA), the content of WSA$_{mi}$ increased and content of WSA$_{ma}$ >3 mm decreased. Higher humus quality (HA : FA ratio) resulted in increase of WSA$_{ma}$ >5 mm and in decrease the other sizes of WSA$_{ma}$, significantly in size class 1–0.25 mm and insignificantly in other micro and macro-aggregates sizes. When all studied soils were evaluated together, higher humus stability positively affected stabilization of WSA$_{mi}$. On the other hand, statistically significant linear (positive) relationships between Q$^{4/6}_{HS}$ and Q$^{4/6}_{HA}$ and WSA$_{ma}$ >3 mm were determined. The same findings were published by Šimanský et al. (2013).

When the studied soils were investigated depending on land use (Table 1), some differences were observed compared to soils evaluated together, however, positive correlations between SOC and WSA$_{ma}$ 5–3 mm were determined. In forest soils, positive correlation between SOC and WSA$_{mi}$ and negative correlation with WSA$_{ma}$ >5 mm were found. Opposite results were obtained in agricultural soils. Higher content of SOC resulted in higher content of WSA$_{ma}$ >3 mm and also lower content of WSA$_{mi}$. In agricultural soils higher humus quality was connected with higher content of WSA$_{mi}$ and lower content of WSA$_{ma}$ compared to forest soils, where higher humus quality was negatively correlated with WSA$_{mi}$. This means that micro-aggregates stability was highly significantly influenced by FA, as well as labile components of SOM. High humus quality had highly significantly negative effect on the content of WSA$_{ma}$, which means that with increased humus quality, the WSA$_{ma}$ stability decreased. The fact that HA was not essential for macro-aggregates stability was confirmed by their negative correlations between WSA$_{ma}$ and the content of HA. On the other hand, the stability of WSA$_{ma}$ 3–0.25 mm was highly positively influenced by FA, therefore we consider that FA is substantial in WSA$_{ma}$ stability in the studied agricultural soils. Since FA is less condensed than HA, being exposed to oxygen and microorganisms they are more susceptible to mineralization that leads to disintegration of soil macro-aggregates. Compared to agricultural soils, the situation in forest soils was considerably different. Increased humus quality had highly significantly positive effect on the content of WSA_{ma} >5 mm but negative on the content of WSA_{ma} <3 mm as well as WSA_{mi}. The obtained results imply that, in the studied forest soil, HA were the most important factors influencing the stability of WSA_{ma} >5 mm, whereas WSA_{ma} in size 3–1 mm and WSA_{mi} were stabilised mainly by fulvic acids. The strongest bindings are formed at the creation of humus substances (Piccolo and Mbagwu, 1990), and they gradually get weaker. A higher content of CL in WSA_{mi} had a positive effect on stabilization of WSA_{mi} in forest soils. This was not observed in agricultural soils. On the other hand, in agricultural soils SOC in WSA positively correlated with WSA_{ma} >3 mm; however, the above-mentioned correlation was not found in forest soils. We concluded that in agricultural soils the stabilization of WSA_{ma} was associated with stable SOM as it has been published in Šimanský et al. (2014). In forest soils, a higher content of CL in WSA_{ma} had a negative effect on the content of WSA_{ma}. However, clay particles can form a protective coatings around the labile forms of organic matter which may inhibit decomposition of the SOM inside aggregates by the bacterial colonies (Oades and Waters, 1991); this has a positive effect on soil structure stability (Le Bissonnais, 1996).

Soil texture is another important factor in aggregation (Lal and Shukla, 2004; Paradelo et al., 2013). Evaluating all soils together, particle-size distribution was not the substantial factor affecting aggregate stability. When all soil types were investigated separately with dependence on land use, particle-size distribution had statistically significant effect on the stability of individual size classes of WSA (Table 2). Soil management practices or land use can influence clay dispersability, in particular via impacts on organic carbon contents and aggregation (Burt et al., 2001; Shaw et al., 2002). He et al. (2005) and Li et al. (2006) proved that sand content (1-0.05 mm) of cropland soils is higher than that of grassland soils. The return of plant residues to grassland soil along with no ploughing results in soil organic carbon enrichment and accelerates formation of fine soil particles, which leads to a relatively higher clay content in grassland soil than cropland soil. In our case, the forest and agricultural soils contained least sand particles in the WSA_{mi}. In agricultural soils, the fraction of coarse sand (>0.25 mm) was more represented in WSA_{ma} over 1 mm and coarse sand was less represented in WSA_{mi}. In forest soils, higher contents of fine sand (0.25–0.05 mm) and coarse silt (0.05–0.01 mm) resulted in higher content of WSA_{ma} 3-0.25 mm. In agricultural soils, coarse silt and clay (<0.002 mm) positively correlated with WSA_{mi} and negatively with WSA_{ma} what means that formation and stabilization of WSA_{ma} is not a function of particle-size distribution alone (relationships are

Table 1 Correlation coefficients between soil organic matter parameters and individual size classes of water-stable aggregates

	SOC	HA	FA	HA : FA	$Q^{4/6}_{HS}$	$Q^{4/6}_{HA}$	SOC in WSA	CL in WSA
Forest soils								
WSA_{mi}	0.984***	-0.331	0.997***	-0.914***	-0.157	-0.385	0.367	0.541*
>5	-0.868***	0.628*	-0.965***	0.997***	0.478	0.671**	-0.388	-0.557*
3-5	0.782***	0.492	0.599*	-0.297	0.640*	0.441	0.146	0.251
1–3	0.489	-0.939***	0.693**	-0.894***	-0.862***	-0.957***	0.331	0.453
1–0.25	0.260	-0.995***	0.495	-0.757***	-0.960***	-0.999***	0.271	0.359
WSA_{ma}	-0.984***	0.331	-0.997***	0.914***	0.157	0.385	-0.367	-0.541*
Agricultural soils								
WSA_{mi}	-0.530*	0.687**	-0.547*	0.996***	-0.673**	-0.668**	-0.498	-0.306
>5	0.656**	-0.793***	0.410	-0.997***	0.549*	0.543*	0.587*	0.357
3-5	0.637*	-0.777***	0.433	-0.999***	0.570*	0.564*	0.573*	0.349
1–3	0.453	-0.620*	0.619*	-0.985***	0.736**	0.731**	0.443	0.274
1–0.25	-0.016	-0.182	0.914***	-0.790***	0.967***	0.965***	0.090	0.067
WSA_{ma}	0.530*	-0.687**	0.547*	-0.996***	0.673**	0.668**	0.498	0.306

*P <0.05; ** P <0.01; *** P <0.001

WSA_{mi} – water-stable micro-aggregates, WSA_{ma} – water-stable macro-aggregates, SOC – soil organic carbon, HA : FA – humic to fulvic acids ratio, $Q^{4/6}_{HS}$ – colour quotient of humic substances, $Q^{4/6}_{HA}$ – colour quotient of humic acids, HA – content of humic acids, FA – content of fulvic acids, SOC in WSA – soil organic carbon in water-stable aggregates, CL in WSA – labile carbon in water-stable aggregates

Table 2 Correlation coefficients between particle-size distribution and individual size classes of water-stable aggregates

	Particle-size distribution in mm					
	>0.25	0.25–0.05	0.05–0.01	0.01–0.002	<0.002	<0.01
Forest soils						
WSA$_{mi}$	-0.758**	0.676**	0.752**	-0.378	0.131	-0.247
>5	0.775***	-0.757**	-0.869***	0.491	-0.014	0.438
3–5	-0.363	0.177	0.136	0.054	0.334	0.300
1–3	-0,622*	0.705**	0.847***	-0.552*	-0.170	-0.631*
1–0.25	-0.488	0.612*	0.754**	-0.526*	-0.241	-0.660**
WSA$_{ma}$	0.758**	-0.676**	-0.752**	0.378	-0.131	0.247
Agricultural soils						
WSA$_{mi}$	-0.658**	0.329	0.611*	0.421	0.713**	0.624*
>5	0.672**	-0.296	-0.590*	-0.518*	-0.738**	-0.688**
3–5	0.671**	-0.302	-0.594*	-0.503	-0.735**	-0.679**
1–3	0.642**	-0.344	-0.616*	-0.361	-0.691**	-0.581*
1–0.25	0.473	-0.378	-0.559*	0.004	-0.480	-0.276
WSA$_{ma}$	0.658**	-0.329	-0.611*	-0.421	-0.713**	-0.624*

*P <0.05; **P <0.01; ***P <0.001
WSA$_{mi}$ – water-stable micro-aggregates, WSA$_{ma}$ – water-stable macro-aggregates

probable more complicated). For example, a several works (Needelman et al., 1999; Neufeldt et al., 2002) reported positive relationship between clay and SOM content. According to Santos et al. (1997), clay flakes form a protective coating against the next colony of bacteria, which would inhibit the decomposition of SOM located inside. This is positively reflected in stabilization of smaller aggregates (Jastrow, 1996). We determined correlations between SOC and CL in WSA and particle-size distribution of individual size classes of WSA. When all soils were evaluated together as well as separately, no significant correlations between SOC and CL contents in WSA and particle-size distribution of WSA were observed.

4 Conclusions

Higher contents of water-stable macro-aggregates than water-stable micro-aggregates were recorded in forest soils in comparison to agricultural soils. We concluded that in agricultural soils the stabilization of water-stable macro-aggregates was associated with stable soil organic matter components. In forest soils, a higher content of labile carbon in water-stable micro-aggregates had a positive effect on stabilization of water-stable micro-aggregates. In forest soils, higher contents of coarse particles resulted in higher contents of water-stable macro-aggregates in size classes 3-0.25 mm. In agricultural soils, the content of fine particles increased the content of water-stable micro-aggregates and the content of coarse particles increased the content of water-stable macro-aggregates.

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