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Soil Structure after 18 Years of Long-term Different Tillage Systems and Fertilisation in Haplic Luvisol

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Abstract

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Soil structure is a key determinant of many soil environmental processes and is essential for supporting terrestrial ecosystem productivity. Management of arable soils plays a significant role in forming and maintaining their structure. Between 1994 and 2011, we studied the influence of soil tillage and fertilisation regimes on the stability of soil structure of loamy Haplic Luvisol in a replicated long-term field experiment in the Dolná Malanta locality (Slovakia). Soil samples were repeatedly collected from plots exposed to the following treatments: conventional tillage (CT) and minimum tillage (MT) combined with conventional (NPK) and crop residue-enhanced fertilisation (CR+NPK). MT resulted in an increase of critical soil organic matter content (St) by 7% in comparison with CT. Addition of crop residues and NPK fertilisers significantly increased St values (by 7%) in comparison with NPK-only treatments. Soil tillage and fertilisation did not have any significant impact on other parameters of soil structure such as dry sieving mean weight diameters (MWD), mean weight diameter of water-stable aggregates (MWD_{WSA}), vulnerability coefficient (Kv), stability index of water-stable aggregates (Sw), index of crusting (Ic), contents of water-stable macro- (WSA_{ma}) and micro-aggregates (WSA_{mi}). Ic was correlated with organic matter content in all combinations of treatments. Surprisingly, humus quality did not interact with soil management practices to affect soil structure parameters. Higher sums of base cations, CEC and base saturation (Bs) were linked to higher Sw values, however higher values of hydrolytic acidity (Ha) resulted in lower aggregate stability in CT treatments. Higher content of K^+ was responsible for higher values of MWD_{WSA} and MWD in CT. In MT, contents of Ca^{2+}, Mg^{2+} and Na^+ were significantly correlated with contents of WSA_{mi} and WSA_{ma}. Higher contents of Na^+ negatively affected St values and positive correlations were detected between Ca^{2+}, Mg^{2+} and Na^+ and Ic in NPK treatments.

Keywords: different soil management; index of crusting; soil organic matter; soil structure; vulnerability coefficient; water-stable aggregates

Luvisols belong to a category of very fertile soils suitable for growing a wide range of crop plants, collectively they are the most commonly utilized soils in agricultural production in Slovakia (12.9% of agricultural land) and cover around of 317 360 ha (Bielek 2014). Luvisols are often referred to as texturally differentiated soils and part of metamorphic soils (Russia), sols lessivés (France), Parabraunerden (Germany), chromosols (Australia) and luvissolos (Brazil). The US nomenclature had them formerly classified as Grey Brown Podzolic soils, but now they belong to Alfisols with high-activity clays. These soils cover an estimated about 500–600 million ha worldwide, mainly in temperate regions such as the East European Plain and parts of the West Siberian Plain in Russia, parts of Central Europe, the North-East

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of the USA, but are also found in the Mediterranean region and in southern Australia.

Many arable soils in the Danube Lowland (Slovakia) are prone to physical and chemical degradation due to their low organic matter content, unfavourable particle-size distribution and deteriorated physical state, most often resulting from a repeated application of incorrect soil management practices. Management of key soil properties such as soil structure is therefore a key consideration when reversing their degradation. Soil structure is a major soil property since it regulates soil functions such as water movement, water content, oxygenation and temperature (Kodešová *et al.* 2015; Neira *et al.* 2015). Soil structure also greatly influences plant germination and root growth (Tormena *et al.* 2016) and is a key determinant of soil quality (Ball & Munkholm 2015). Soil structure can be modified by soil management practices which significantly influence aggregation and structural development of soils (Bronick & Lal 2005). On the one hand, conventional tillage may enhance the disruption of physical properties (Šimanský *et al.* 2016a) included soil structure (Beare *et al.* 1994; Šimanský *et al.* 2016b). On the other hand, conservation tillage and residue management are thought to represent viable options for enhancing soil organic carbon stabilization by improving soil aggregation (Choudhury *et al.* 2014). Wang *et al.* (2015) indicate that intensive tillage has a twofold impact upon the soil: aggregate redistribution due to the soil transfer process and the mechanical breakage of macroaggregates. It is suggested that the use of reduced tillage is not only an effective method for diminishing soil erosion, but also a feasible strategy for improving soil structure on hill slopes. Crop residue retention is important for sequestering soil organic carbon (SOC), controlling soil erosion, and improving soil quality (Blanco-Canqui & Lal 2004). Repeated application of organic residues and fertilisation can alter soil physical properties (Baldock *et al.* 1994).

Long-term field experiments are essential for the assessment of tillage and fertilisation effects on soil fertility. They provide the best possible means to observe changes in soil properties (Neugschwandtner *et al.* 2014). As mentioned above, soil aggregation can be improved by management practices such as reduction of agro-ecosystem disturbance, improvement of soil fertility, increase in organic inputs, enhancement of plant cover, and decrease in SOC decomposition rate (Bronick & Lal 2005). The objectives of this study therefore were to (*i*) quantify the extent to which tillage and manure treatments influence soil structure stability in a Haplic Luvisol and to (*ii*) determine the relationship between chemical properties, soil organic parameters and parameters of soil structure stability as driven by soil tillage regime and fertilisation.

MATERIAL AND METHODS

This study is based on a long-term experiment established in 1994 at the experimental station of Slovak Agriculture University Nitra, in Dolná Malanta locality (lat. 48°19'00''; lon. 18°09'00''). The soil at the site is classified as loamy Haplic Luvisol (WRB 2014) with soil texture determined as: 36% of sand, 49% of silt and 15% of clay. Soil carbon content at the start of the experiment was 12.9 g/kg, while the cation exchange capacity was 14.7 cmol(p^+)/kg, base saturation percentage reached 92.6% and active pH of the soil was 6.96. The local climate is warm and very dry, with mean annual temperature of 9.8°C and rainfall of 573 mm.

The experimental field (187 × 44 m) is divided into five blocks (A, B, C, D and E), each 35 m wide. Each block was divided into nine rows of 3 m, with a protection belt of 3 m between individual zones. Every block was replicated four times, a schematic layout of the experimental field is shown in Figure 1. The field experiment had the following annual crop rotation: (1) red clover (*Trifolium pratense* L.), (2) pea (*Pisum sativum* L. subsp. *hortense* (Neitr.), (3) winter wheat (*Triticum aestivum* L.), (4) maize (*Zea mays* L.), and (5) spring barley (*Hordeum vulgare* L.). A full-factorial experimental layout of tillage (3 levels) and fertilisation (3 levels) was applied to subplots within each replicate block. Tillage treatments were represented by conventional tillage (CT, tillage depth 0.22–0.25 m), reduced tillage (RT, cultivation depth 0.12–0.15 m) and minimum tillage (MT, operation depth 0.10–0.12 m). Fertilisation treatments were as follows: (1) 0 without fertilization, (2) CR+NPK – crop residues added together with NPK fertilizers, (3) NPK – with added NPK fertilizers. Plant residues were returned to the soil in CR+NPK variants. Fertilisation was applied annually with the mean dose reaching N 80 kg/ha, P (P_2O_5) 45 kg/ha and K (K_2O) 72 kg/ha. Fertilizers used in the experiment were labelled as nitre ammonium with dolomite (LAV 27), potassium chloride (KCl) and triple superphosphate ($Ca(H_2PO_4)_2 \cdot H_2O$). The doses of NPK were calculated by balance method.

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For the purpose of this study, soil samples were collected twice a year (spring and autumn) from the depth of 0–0.25 m in two types of soil tillage (CT and MT) and two variants of fertilisation (CR+NPK and NPK). In each combination of treatments, three different sampling locations were chosen randomly. Soil samples were collected with a corer and pooled to generate an average sample. Samples were air-dried in the laboratory at air temperature and standard soil analyses were used for determination of soil pH in H_2O (1 : 2.5 – soil/distilled water) and KCl (1 : 2.5 – soil/1 M KCl) and sorption parameters such as hydrolytic acidity (Ha), sum of base cations (SBC) – included individual exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), cation exchange capacity (CEC), and base saturation (Bs) (Hrivňáková *et al.* 2011). Soil organic carbon was determined according to the Tyurin method (Dziadowiec & Gonet 1999) and the composition of humus substances (C_{HS}), humic (C_{HA}) and fulvic (C_{FA}) acids was determined according to Belchikova and Kononova (Dziadowiec & Gonet 1999). The absorbance of humus substances and humic acids was measured at 465 and 650 nm to calculate the colour quotient $Q_{4/6}^{HS}$ and $Q_{4/6}^{HA}$. Soil samples for determination of soil structure parameters were collected with the aid of a spade to maintain the soil aggregation. In laboratory, large clods were gently broken up along natural fracture lines, followed by air-drying at the laboratory temperature. Soil samples were sieved (dry and wet sieving) to the following seven size fractions: > 7, 7–5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25 mm. Percentages of water-stable aggregates (WSA) were determined by the Baksheev method (Vadjunina & Korchagina 1986). The size fractions of WSA were as follows: > 5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25 mm. The remaining material except for water-stable microaggregates was quantified in each sieve. The microaggregate fraction was calculated as the difference between the total weight of the soil sample and the sums of macroaggregates. Fractions of WSA larger than 0.25 mm (> 0.25 mm) were considered water-stable macroaggregates (WSA_{ma}) and fractions smaller than 0.25 mm (< 0.25 mm) water-stable microaggregates (WSA_{mi}). On the basis of dry and wet sieving samples, we then calculated values of mean weight diameters for dry sieving (MWD), mean weight diameter of water-stable aggregates (MWD_{WSA}), vulnerability coefficient (Kv) by Valla *et al.* (2000) as well as the stability index of water-stable aggregates (Sw) by Henin, index of crusting (Ic) (Lal & Shukla 2004) and critical soil organic matter content (St) according to Pieri (1991).

Statistical analyses were performed using Statgraphics Centurion XV.I programme (Statpoint Technologies, Inc., USA). A one-way ANOVA model and the

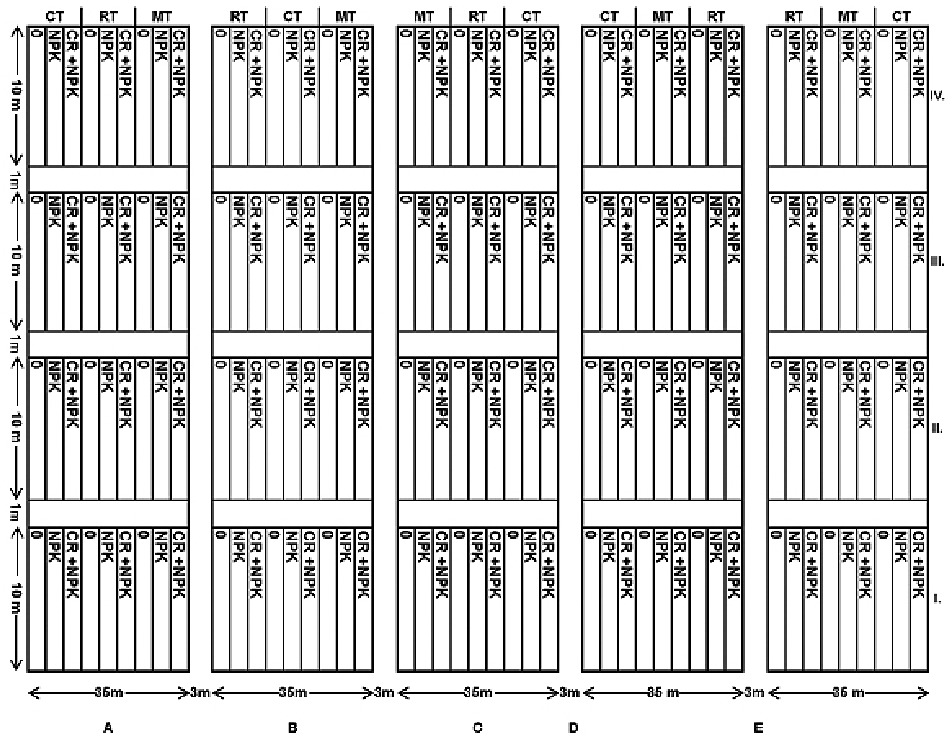

Figure 1. Schematic layout of the experimental field

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least significant difference tests were used to analyse the significance of differences in soil structure parameters between conventional and minimum tillage systems, as well as two levels of fertilisation. We used correlation analysis to determine the relationships between soil organic matter parameters, chemical properties and parameters of soil structure stability. Correlation coefficients were tested for significance at $P < 0.05$.

RESULTS

Soil structure parameters. Parameters of soil structure affected by soil tillage and fertilisation are presented in Figure 2A–H. Soil tillage and fertilisation had a statistically significant effect on St, which increased by 7% in MT in comparison with CT. The incorporation of crop residues, together with NPK fertilizers (CR+NPK), significantly increased St values by 7% in comparison with NPK treatment. A better soil structure stability was achieved in MT than in CT, as indicated by the Kv values of 5.11 and 5.15, respectively. A similar picture was revealed when looking at the presence and proportion of water-stable aggregates (Figure 2D, E). The mean value of Ic was 5% higher under NPK compared to CR+NPK, leading to higher Kv in the NPK treatment. Addition of just NPK fertilizers increased MWD_{WSA} and MWD by 9% and by 4% when compared to CR+NPK, respectively. The value of Sw (0.85) was slightly higher in CR+NPK than in NPK (0.82) treatments.

Relationships between chemical properties and soil structure parameters. We did not find any significant correlations between SOC and Kv, WSA_{mi}, WSA_{ma}, Sw, MWD_{WSA} and MWD attributable to the application of tillage or fertiliser treatments. On the other hand, we found statistically significant correlations between SOC and St and Ic under all tillage and fertilisation regimes (Table 1). The content of C_{HS} negatively correlated with MWD only in MT and in NPK treatments. A higher content of C_{HA} affected WSA_{mi} content positively and WSA_{ma} content negatively under both CT and in CR+NPK

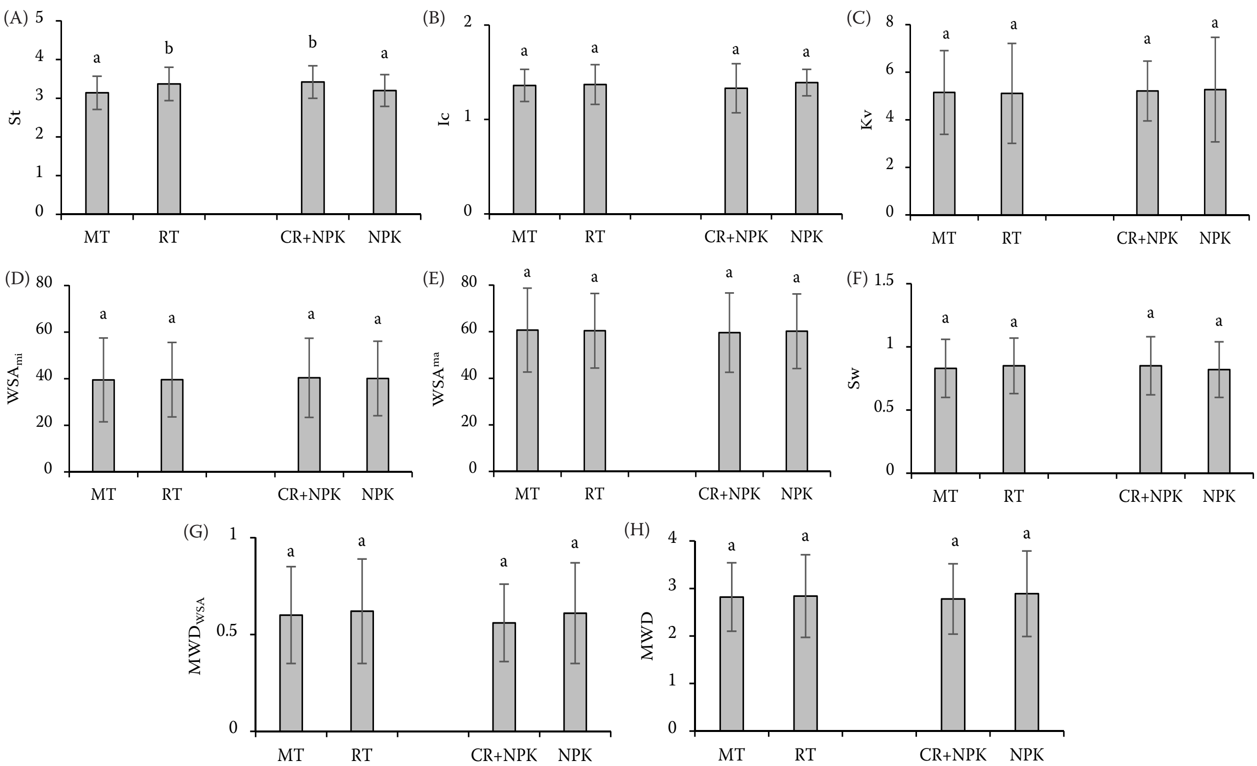

Figure 2. Analyses of variance of soil structure parameters: (A) critical level of soil organic matter, (B) index of crusting, (C) vulnerability coefficient, (D) content of water-stable microaggregates, (E) content of water-stable macroaggregates, (F) stability index of water-stable aggregates, (G) mean weight diameter of water-stable aggregates, (H) dry sieving mean weight diameters

Different letters between columns (a, b) indicate that treatment means are significantly different at $P < 0.05$ according to the LSD multiple-range test

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Table 1. Correlation coefficients between soil organic matter parameters and parameters of soil structure

	SOC	C_{HS}	C_{HA}	C_{FA}	$C_{HA}:C_{FA}$	$Q_{4/6}{}^{HS}$	$Q_{4/6}{}^{HA}$
Conventional tillage							
St	0.672***	ns	ns	ns	ns	ns	ns
Ic	–0.377**	ns	ns	ns	ns	ns	ns
Kv	ns	ns	ns	ns	ns	ns	0.291*
WSA_{mi}	ns	ns	0.314*	ns	ns	0.314*	ns
WSA_{ma}	ns	ns	–0.311*	ns	ns	–0.324*	ns
Sw	ns	ns	ns	ns	ns	–0.314*	ns
MWD_{WSA}	ns	ns	–0.294*	ns	ns	ns	ns
MWD	ns	ns	ns	ns	ns	ns	ns
Minimum tillage							
St	0.689***	ns	ns	ns	ns	ns	ns
Ic	–0.287*	ns	ns	ns	ns	ns	ns
Kv	ns	ns	ns	ns	ns	ns	ns
WSA_{mi}	ns	ns	ns	ns	ns	ns	ns
WSA_{ma}	ns	ns	ns	ns	ns	ns	ns
S_w	ns	ns	ns	ns	ns	ns	ns
MWD_{WSA}	ns	ns	ns	ns	ns	ns	ns
MWD	ns	–0.444***	–0.286*	–0.304*	ns	ns	ns
NPK treatments							
St	0.708***	ns	ns	ns	ns	ns	ns
Ic	–0.650***	ns	ns	ns	ns	ns	ns
Kv	ns	ns	ns	ns	ns	ns	ns
WSA_{mi}	ns	ns	ns	ns	ns	ns	ns
WSA_{ma}	ns	ns	ns	ns	ns	ns	ns
S_w	ns	ns	ns	ns	ns	ns	ns
MWD_{WSA}	ns	ns	ns	ns	ns	0.462**	ns
MWD	ns	–0.353*	ns	ns	ns	ns	ns
CR+NPK treatments							
St	0.666***	ns	ns	ns	ns	ns	ns
Ic	–0.688***	ns	ns	ns	ns	ns	ns
Kv	ns	ns	ns	ns	ns	ns	ns
WSA_{mi}	ns	ns	0.356*	ns	ns	ns	ns
WSA_{ma}	ns	ns	–0.356*	ns	ns	ns	ns
S_w	ns	ns	ns	ns	ns	ns	ns
MWD_{WSA}	ns	ns	–0.431**	ns	ns	ns	ns
MWD	ns	ns	–0.403*	ns	ns	ns	ns

ns – not significant; SOC – total soil organic carbon; C_{HS} – humic substances; C_{HA} – humic acids; C_{FA} – fulvic acids; $C_{HA}:C_{FA}$ – humic to fulvic acids ratio; $Q_{4/6}{}^{HS}$ – colour quotient of humic substances; $Q_{4/6}{}^{HA}$ – colour quotient of humic acids; St – critical level of soil organic matter; Ic – index of crusting; Kv – vulnerability coefficient; WSA_{mi} – content of water-stable microaggregates; WSA_{ma} – content of water-stable macroaggregates; Sw – stability index of water-stable aggregates; MWD_{WSA} – mean weight diameter of water-stable aggregates; MWD – dry sieving mean weight diameters

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Table 2. Correlation coefficients between chemical properties and soil structure parameters

	Ha	SBC	CEC	BS	pH_{H_2O}	pH_{KCl}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
Conventional tillage										
St	0.306*	–0.327**	–0.295*	–0.285*	–0.444***	–0.628***	–0.483***	–0.490***	–0.682***	ns
Ic	ns	ns	ns	ns	ns	0.279*	0.459***	0.429**	0.385**	ns
Kv	ns	ns	ns	ns	ns	ns	ns	–0.356**	ns	ns
WSA_{mi}	0.479***	–0.424**	–0.358**	–0.467***	–0.426**	–0.509***	–0.271*	–0.372**	–0.393**	–0.393**
WSA_{ma}	–0.482***	0.427**	0.360**	0.471***	0.434**	0.518***	ns	0.361**	0.409**	0.380**
Sw	–0.386**	0.348**	0.296*	0.380**	0.345**	0.353**	ns	ns	0.280*	0.349**
MWD_{WSA}	–0.351**	ns	ns	0.310*	ns	0.269*	ns	0.339*	ns	0.284*
MWD	–0.292*	ns	ns	0.265*	0.356**	0.321*	ns	ns	ns	0.474***
Minimum tillage										
St	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Ic	ns	ns	ns	ns	ns	ns	0.365**	0.377**	ns	ns
Kv	ns	ns	ns	ns	ns	ns	–0.283*	–0.403**	ns	ns
WSA_{mi}	ns	ns	ns	ns	ns	ns	–0.300*	–0.380**	–0.322*	ns
WSA_{ma}	ns	ns	ns	ns	ns	ns	0.300*	0.380**	0.322*	ns
Sw	ns	ns	ns	ns	ns	ns	ns	0.271*	ns	ns
MWD_{WSA}	ns	ns	ns	ns	ns	ns	0.334*	0.352**	ns	ns
MWD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
NPK treatments										
St	ns	ns	ns	ns	ns	ns	ns	ns	–0.387*	ns
Ic	ns	ns	ns	ns	ns	ns	0.438**	0.521**	0.374*	ns
Kv	ns	ns	ns	ns	ns	ns	ns	–0.432*	ns	ns
WSA_{mi}	ns	ns	ns	–0.370*	ns	ns	ns	–0.423*	–0.357*	ns
WSA_{ma}	ns	ns	ns	0.369*	ns	ns	ns	0.405*	0.383*	ns
Sw	ns	ns	ns	0.373*	ns	ns	ns	ns	ns	ns
MWD_{WSA}	ns	ns	ns	ns	ns	ns	ns	0.476**	0.135	ns
MWD	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.387*
CR+NPK treatments										
St	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.430**
Ic	ns	ns	ns	ns	ns	ns	0.388*	ns	ns	ns
Kv	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WSA_{mi}	ns	ns	ns	ns	ns	ns	ns	ns	ns	–0.392*
WSA_{ma}	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.392*
Sw	ns	ns	ns	ns	0.340*	ns	ns	ns	ns	0.515**
MWD_{WSA}	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.427*
MWD	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.481**

ns – not significant; Ha – hydrolytic acidity; SBC – sum of base cations; CEC – cation exchange capacity; BS – base saturation; St – critical level of soil organic matter; Ic – index of crusting; Kv – vulnerability coefficient; WSA_{mi} – content of water-stable microaggregates; WSA_{ma} – content of water-stable macroaggregates; Sw – stability index of water-stable aggregates; MWD_{WSA} – mean weight diameter of water-stable aggregates; MWD – dry sieving mean weight diameters

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treatments. Significantly negative correlations were found between C_{HA} and MWD_{WSA} in CT and between C_{HA} and MWD in MT. In comparison with NPK, we observed significantly negative correlations between C_{HA} and MWD_{WSA} and MWD in CR+NPK treatment. The degree of humification ($C_{HA} : C_{FA}$) did not have any significant effects on soil structure parameters under any of the tested soil management practices. Higher humic substance stability supports the intensive aggregation of WSA_{mi} in CT, where it was also linked to a higher content of WSA_{ma} and higher aggregate stability. At the same time, higher presence of stable humic acids decreased Kv values. In MT however, no significant correlations between humic substance content and aggregate stability were observed. The same trend was observed in CR+NPK treatments. In NPK, the higher humic substance stability resulted in an increase of MWD_{WSA} values.

Under CT, we found several significant correlations between sorption parameters and soil structure parameters of Haplic Luvisol (Table 2). Sorption parameters and exchangeable cation content were strongly correlated with WSA_{mi} and WSA_{ma} content. Strong correlations were also observed between soil pH and the contents of exchangeable cations and St values. Higher contents of SBC, CEC and Bs resulted in higher Sw values, however higher values of Ha resulted in lower aggregate stability in CT treatments. Surprising positive correlations between Na^+ and K^+ and Sw were determined. In CT treatments, significantly negative correlations were also observed between Ha and MWD_{WSA} and MWD (r = –0.351 and –0.291, $P \leq 0.01$ and $P \leq 0.05$, respectively). Both values of Bs and soil pH positively correlated with MWD_{WSA} and MWD. Higher content of K^+ was responsible for higher values of MWD_{WSA} and MWD in CT.

However, correlations between sorption properties and soil structure parameters of Haplic Luvisol under RT indicated a different trend (Table 2). Several significant correlations between soil pH and sorption parameters and soil structure indicators driven by MT regime were observed. Ca^{2+} and Mg^{2+} were negatively correlated with Kv values in MT. The contents of Ca^{2+}, Mg^{2+} and Na^+ were also significantly correlated with WSA_{mi} and WSA_{ma} in MT, however a stronger correlation was found under CT (Table 2). On the other hand, more significant correlations between Ca^{2+} and Mg^{2+} and MWD_{WSA} than in CT were found under MT. As shown in Table 2, a few significant correlations were found between Ha as well as Bs values and WSA_{mi}, WSA_{ma} and Sw in treatments with the addition of NPK fertilisers only. Higher contents of Na^+ negatively affected St values. At the same time, we detected positive correlations between Ca^{2+}, Mg^{2+} and Na^+ and Ic in NPK treatment. In this treatment, higher content of Mg^{2+} and higher content of Na^+ resulted in larger WSA_{ma} values (Table 2). A significant correlation was found between Mg^{2+} and MWD_{WSA} (r = 0.476, $P \leq 0.01$). In comparison with NPK treatments, some significant correlations between sorption parameters and soil structure parameters of Haplic Luvisol were determined in CR+NPK treatments. On the other hand, in comparison with NPK, in CR+NPK treatments the content of K^+ correlated with St, WSA_{mi}, WSA_{ma}, Sw, MWD_{WSA} and MWD (r = 0.430, –0.392, 0.392, 0.515, 0427, respectively).

DISCUSSION

Macroaggregate stability is often claimed to be affected by soil management practice (Bronick & Lal 2005; Bartlová *et al.* 2015). Incorporation of crop residues into the soil is a very important tool for increasing macroaggregate stability (Baldock *et al.* 1994; Blanco-Canqui & Lal 2004). These observations were confirmed by this study, the addition of crop residues in combination with NPK application had a positive effect on St values after 18 years (Figure 2A). Under CR+NPK treatments, values of St were 7% higher than under NPK addition only. The application of mineral fertilisers may decrease soil organic matter content, which is often followed by lower aggregation. In our case, the likely reason for the decrease of SOM was the application of N fertiliser (LAV 27) in ammonium form which has been shown to negatively affect soil structure (Haynes & Naidu 1998). The higher ion concentration in the soil can result in higher clay dispersion and aggregate breakdown in fertilised soils (Whalen & Chang 2002).

The relationship between SOC and soil structure parameters was previously studied in different soil types, climate conditions and under varying soil management practices (e.g. Bartlová *et al.* 2015; Rajkai *et al.* 2015; Schacht & Marschner 2015), with contradictory results. For instance, Itami and Kyuma (1995) and Igwe *et al.* (1999) showed that SOC is not the most important binding agent responsible for aggregation. Yilmaz and Sönmez (2017) mentioned a very strong linear relationship between SOC and MWD, an observation in direct

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contrast with our results (Table 1). We did not find any significant relationship between SOC and Kv, WSA_{mi}, WSA_{ma}, Sw, MWD_{WSA} and MWD, nor did we see any modification of this relationship by soil tillage and fertilisation. However, we observed negative correlations between C_{HS} and MWD in MT and NPK treatments. In addition, we found statistically significant correlations between SOC and St and Ic under all soil management practices. The parameters of St and Ic are affected by particle-size distribution, SOC (Pieri 1991; Lal & Shukla 2004) and different soil management practices. Our results show that higher content of C_{HA} is related to WSA contents under CT and CR+NPK treatment. Strong correlations were detected between C_{HA} and MWD_{WSA} in CT and between C_{HA} and MWD in MT. In comparison with NPK, we observed negative correlations between C_{HA} and MWD_{WSA} and MWD in CR+NPK treatment. Surprisingly, some correlations were between the C_{HA}:C_{FA} ratio and soil structure parameters. Oades (1984) posits that not all organic compounds in the soil are responsible for aggregation. Different forms of organic matter stabilize aggregates of different sizes and sometimes may have no impact on the soil aggregation whatsoever or indeed may lower the aggregation potential. For example, the addition of anionic organic compounds (citrates, oxalates and acetates) to the soil can increase a dispersion of clay suspension (Goldberg *et al.* 1990; Itami & Kyuma 1995).

Boix-Fayox *et al.* (2001) claimed that larger aggregates are formed in soils with higher pH. This is in partial agreement with our results, as we found better indication of soil structure with increasing soil pH and SBC, but only under the CT treatment (Table 2). Dimoyiannis *et al.* (1998) connected aggregate stability with CEC, but Nelson *et al.* (1999) contended that this connection drives aggregate dispersion. In our case, higher values of CEC improved soil aggregate stability (r = 0.296; $P \leq 0.05$) in CT treatments. Ca^{2+}, Mg^{2+} and Na^{+} contents were significantly correlated with the contents of WSA_{mi} and WSA_{ma}, however, a higher correlation was found in CT when compared to MT (Table 2). In general, Ca^{2+} is more effective in improving the soil structure than Mg^{2+} (Zhang & Norton 2002), Na^{+} can affect clay dispersion (Marchuk *et al.* 2012), with resulting destruction of soil aggregates. In this experiment, the proportion of the sum of base cations as Ca^{2+} was highest under CT and lowest under MT (Šimanský & Tobiašová 2012), therefore we identified stronger correlations between Ca^{2+}, Mg^{2+} and soil structure parameters in CT than in MT treatments. Our results show that a higher content of Na^{+} results in higher contents of WSA_{ma} and in lower contents of WSA_{mi} in CT, MT and NPK treatments. This effect has not been observed in CR+NPK. Effects of K^{+} on structure parameters in CT and CR+NPK treatments were positive when compared with MT and NPK treatments, respectively. This effect can be related with higher contents of K^{+} in CT and in CR+NPK, as published by Šimanský and Tobiašová (2012).

CONCLUSION

Soil structure parameters vary in time and the attributes observed at any given time reflect the accumulation of interacting factors over time. We did not observe any significant changes in parameters indicative of soil structure under any soil management practices, with the exception of St values. The correlations between SOC and soil structure indicators however show that (1) MT rather than conventional tillage and (2) ploughed crop residues together with NPK fertilizers rather than NPK only treatment are better for the management of favourable soil structure of Haplic Luvisol. We saw higher contents of humic acids and humic substances in CT and treatments with incorporated crop residues with NPK fertilizers. Since these compounds stimulate soil aggregate stability and support the intensive aggregation of water-stable aggregates, it is likely that CT and crop residues+NPK treatments are beneficial. In CT, aggregation processes were supported by better sorption parameters of soil compared to other soil management practices.

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