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SOIL ORGANIC-MATTER IN WATER-STABLE AGGREGATES UNDER DIFFERENT SOIL-MANAGEMENT PRACTICES

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An experiment of different management practices in a commercial vineyard, which was established in 2006 in the locality of Nitra-Dražovce, Slovakia on Rendzic Leptosol, was used to evaluate the dynamics of soil organic-matter parameters during the years 2008–2015. The following treatments were established: 1. G (grass without fertilisation as control), 2. T (tillage), 3. T+FYM (tillage + farmyard manure), 4. G+NPK3 (grass + 3rd intensity of fertilisation for vineyards: it means 125 kg/ha N, 50 kg/ha P, 185 kg/ha K), and 5. G+NPK1 (grass + 1st intensity of fertilisation for vineyards: it means 100 kg/ha N, 30 kg/ha P, 120 kg/ha K). The results showed that the soil-management practices in the vineyard significantly influenced the soil organic carbon in water-stable aggregates (SOC in WSA). The content of SOC in WSA_{ma} increased on average in the following order: T < G < G+NPK1 < G+NPK3 < T+FYM. Intensive soil cultivation in the T treatment resulted in a statistically significant build-up of SOC in WSA_{ma} at an average rate of 1.33, 1.18, 0.97, 1.22 and 0.76 g/kg/y across the size fractions > 5 mm, 5–3 mm, 2–1 mm, 1–0.5 mm and 0.5–0.25 mm, respectively. The content of non-labile carbon reflected the contents of SOC in WSA. The highest labile carbon (C_L) in WSA_{ma}, as compared to others, was found in T+FYM. Overall, application of higher NPK doses resulted in higher content of C_L in WSA_{ma} compared with the lower applications of NPK. On the other hand, lower applications of NPK to soil increased the content of C_L in WSA_{mi}, as compared to G+NPK3.

Key words: soil organic carbon, labile carbon, non-labile carbon, soil structure, soil fertility

Soil organic-matter (SOM) plays an important role in plant-nutrient cycling, increasing yields and improving the physical, chemical and biological properties of soils (Bhattacharyya *et al.* 2010; Gaida *et al.* 2013) and the impact varies across space and time and is a result of the influence of many environmental and anthropogenic factors (Jonczak 2014). For example, intensive cultivation leads to loss of SOM (Khorramdel *et al.* 2013) while reduced tillage increases SOM (Šimanský *et al.* 2008). The results of Tong *et al.* (2014) indicated that application of manure had the highest sequestration rate of total SOC in comparison to mineral fertilisers. Triberti *et al.* (2008) found that continuous additions of organ-

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ic material to the soil led to a SOC build up at rates 0.16–0.26 t C/ha/y over a 22 year period. Purakayastha *et al.* (2008) reported the rates of SOC build-up in the soil up to a level of 1.0 Mg/ha/y due to NPK + farmyard application under a maize-wheat-cowpea cropping system. Abdollahi *et al.* (2014) showed the rate of SOC due to added organic fertilisers to be between 220–240 kg C/ha/y. All the information about the increase or decline of C is from different soils. However, the determination of carbon pools in aggregates provides important information on soil C sequestration processes and mineralization mechanisms in aggregate size fractions that could be used to protect SOC by using appropriate soil and crop management practices (Whalen & Chang 2002). Water-stable aggregates may protect the carbon inside of aggregates more intensively than aggregates with low resistance against destructive influence of water (Šimanský & Bajčan 2014) which is also an effective strategy to mitigate global climate change (Paustian *et al.* 1997), whilst sustaining soil health. Changes in land use significantly influence the carbon cycle. An important factor of SOM stabilization is a favourable soil structure (Berhe & Kleber 2013; Chaplot & Cooper 2015). This is because SOM is one of the most significant binding agents which is responsible for the association of mineral particles within the aggregates (Rabbi *et al.* 2015).

Vineyard soils are strongly influenced by anthropogenic activities. Before establishing a vineyard, the original soil type is transformed. There is a change in the structural conditions and capacity of the soil to retain the organic carbon. Therefore, understanding the dynamics and mechanism of carbon sequestration in the water-stable aggregates under different management practices in vineyard soils could be a primary way to improve the soil fertility. This will sustain the grape yield production around the world, and in Slovakia in particular.

The objectives of our study were: (i) to determine C changes in the size fractions of water-stable aggregates under the different management practices in a vineyard; (ii) to determine the rate of C input into water-stable aggregates under different management practices over the period of 8 years.

MATERIAL AND METHODS

The study was carried out in a commercial vineyard located in Nitra-Dražovce (48°21'6.16"N; 18°3'37.33"E) in Nitra wine-growing region of Slovakia. The climate is temperate with an average annual rainfall of 550 mm and with the mean annual temperature being ≥ 10°C. The soil had developed on limestone and dolomite and is classified as Rendzic Leptosol (WRB 2014). The soil was analysed prior the vineyard establishment (spring 2000) and contained 17.0±1.6 g/kg of soil organic carbon, 1867±103 mg/kg of total nitrogen and had a pH_{H2O} value of 7.18±0.08, with the base saturation percentage being 99.3±0.01%. The content of

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The various treatments imposed in the vineyard (Nitra-Drážovce)

Treatment	Description
Control (G)	Sown grass in the rows and between vine rows, without fertilisation.
Tillage (T)	Every year medium tilth to the depth of 25 cm with intensive cultivation (three times on average, without fertilisation) between vine rows during the growing season.
Tillage + application of farmyard manure (T+FYM)	Medium tilth to the depth of 25 cm with application of farmyard manure (FYM) in a dose of 40 t/ha applied in autumn 2005, 2009 and 2012 with intensive cultivation between vine rows during growing season.
Application of fertilisers in 3rd intensity for vineyards according to Fecenko and Ložek (2000) (G+NPK3)	There was used Duslofert Extra 14-10-20-7 fertiliser with the real doses of nutrients applied in the treatment being 125 kg/ha N, 50 kg/ha P, 185 kg/ha K. Split application of fertilisers was applied with 2/3 of fertilisers applied in the spring (bud burst – on March) and 1/3 during the flowering stage (on May). The grass was sown in and between the vine rows.
Application of fertilisers in 1st intensity for vineyards according to Fecenko and Ložek (2000) (G+NPK1)	There was used Duslofert Extra 14-10-20-7 fertiliser with the real doses of nutrients applied in the treatment being 100 kg/ha N, 30 kg/ha P, 120 kg/ha K. The doses of nutrients were split with 1/2 applied in the spring (bud burst – on March) and 1/2 during flowering (on May). The grass was sown in and between the vine rows.

sand, silt and clay was 57%, 33% and 10%, respectively.

A variety of grasses (*Lolium perenne* 50% + *Poa pratensis* 20% + *Festuca rubra commutata* 25% + *Trifolium repens* 5%) were sown as grass strip between the vineyard rows in 2003. The experiment with different soil management practices (5 treatments) was initiated in 2006, and laid out on a randomized complete block design with four replicates. The investigated treatments are presented in Table 1. Soils samples (0–0.25 m) were taken from 4 random locations within each treatment every spring during years 2008–2015. Soil samples were then mixed together to form an average sample for each treatment. Large clods were gently broken up along natural fracture lines, and then air-dried in the laboratory to achieve undisturbed soil samples for the determination of the individual size fractions of aggregates. The Baksheev method for aggregate separation was adopted from Vadjunina and Korchagina (1986). Seven aggregate-size fractions were separated by wet-sieving of the soil through the series of six sieves. Briefly, the soil sample (30 g) was covered with distilled water with the water level 1 cm above aggregates. Two hours later, the sample was transferred to the top sieve (>5 mm) in a cylindrical container (Baksheev device), which had been filled with distilled water. The cylinder was hermetically closed and the sample was sieved for 12 minutes. The size fractions of WSA were the following: >5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25 mm as water-stable macro-aggregates (WSA_{ma}) and <0.25 mm as micro-aggregates (WSA_{mi}). The material retained was quantified in each sieve, except for the micro-aggregates (<0.25 mm). Their content was calculated as difference between total weight of soil sample and sums of the macro-aggregates (>0.25 mm). The content of soil organic carbon (SOC) in the individual size fractions of water-stable aggregates (WSA) was determined using the wet combustion method by oxidation of organic matter using a mixture of 0.07 M H_2SO_4 and $K_2Cr_2O_7$ with titration using 0.01 M Mohr's salt. This is described in Dziadowiec and Gonet (1999). The labile carbon content (C_L) was extracted from samples containing 1 g of individual size fractions of WSA by shaking in 50 mL of 0.005 M $KMnO_4$ for 2 h. After centrifugation, the C_L was determined with titration using 0.05 M Mohr's salt (Loginow *et al.* 1987). Non-labile carbon (C_{NL}) was calculated according to equation (1):

$$C_{NL} = SOC - C_L \quad (1)$$

where: SOC (in g/kg) is the organic carbon content and C_L (in g/kg) is the labile carbon content

The statistical processing of the data included checking of the data for normality and later by using one-way analysis of variance (ANOVA) using Statgraphics Centurion XV.I statistical software (Statpoint Technologies, Inc., USA). Significant differences between the treatment means of the three replicates were identified using a least significant difference (*LSD*) at $p < 0.05$. The correlations between SOM in WSA and WSA contents were then determined. A linear model was used to evaluate the trends of SOC, C_{NL} and C_L under the different soil-management practices of vineyard during the period of 8 years.

RESULTS AND DISCUSSION

Water-stable aggregates

The distribution of aggregate sizes under the different soil-management practices of the vineyard is shown in Figure 1. If the results of WSA were evaluated as an average of WSA_{mi} and WSA_{ma} there would not be any significant differences between management practices. However, if they were evaluated by individual aggregate sizes of $WSA_{ma,}$ the one-way ANOVA analysis showed significant differences between treatments, for size fractions of WSA_{ma} >5mm, 5–3 mm, 1–0.5 mm and 0.5–0.25 mm. The lowest average content of WSA_{ma} was determined in T treatment. There have been reported a negative impacts of intensive soil cultivation on the content of water-stable aggregates (Wang *et al.* 2015). Tillage was held responsible for the disruption of soil aggregates (Plante & McGill 2002). On the other hand, the highest average content of WSA_{ma} was found in the G+NPK3 treatment and then with G > T+FYM > G+NPK1. The complexity of the chemical and physical effects of fertilisers has resulted in variable effects of fertilisation on the aggregates. There have been reported negative impacts of the use mineral fertilisers on aggregate resistance (Czachor *et al.* 2015). However, the fertiliser application generally improves the soil aggregation (Haynes & Naidu 1998) due to increasing macro-aggregation and enhanced resistance to slaking (Whalen & Chang 2002).

Soil organic carbon in water-stable aggregates

Our study has shown that soil-management practices significantly influenced SOC in WSA (Table 2). The content of SOC was lower in WSA_{mi} than in WSA_{ma} across all treatments. Six *et al.* (2004) pointed out that at the lowest depletion of C content in small macro-aggregates and micro-aggregates, could be due to a better protection of C in these aggregate sizes (Rabbi *et al.* 2015). The lowest content of SOC in WSA_{mi} was found here in T and the highest in G+NPK1 treatment. There was observed an increase of the C concentration for larger size fractions of WSA_{ma}, which is in line with other studies where the linear increase of C concentration was found to be in larger aggregates size classes (Biswas *et al.* 2009). Overall, the highest average SOC content in WSA_{ma} was in T+FYM, while the lowest ones were in the T treatment. The SOC content in WSA_{ma} increased in the following order: T < G < G+NPK1 < G+NPK3 < T+FYM. Several authors have also confirmed a loss of C in the soil (Khorramdel *et al.* 2013), and in the aggregates (Abdollahi *et al.* 2014), under intensive tillage systems. This is logical because the tillage disrupts the soil and supports mineralization processes in the soils (Polidori *et al.* 2008). Application of organic and mineral fertilisers increased the average content of SOC in WSA_{ma} by 22%, 9% and 6% in T+FYM, G+NPK3 and G+NPK1, respectively, as compared to control (Table 2).

Table 3 provides the dynamics of SOC at the individual aggregate sizes of $WSA_{ma,}$ under the different soil-management practices during the whole studied period. Intensive cultivation of the soil in the T treatment significantly increased the SOC in WSA_{ma} at an average rate of 1.33, 1.18, 0.97, 1.22 and 0.78 g/kg/y across the size fractions > 5 mm, 5–3 mm, 2–1 mm, 1–0.5 mm and 0.5–0.25 mm, respectively. Expressed as percentage this is an in-

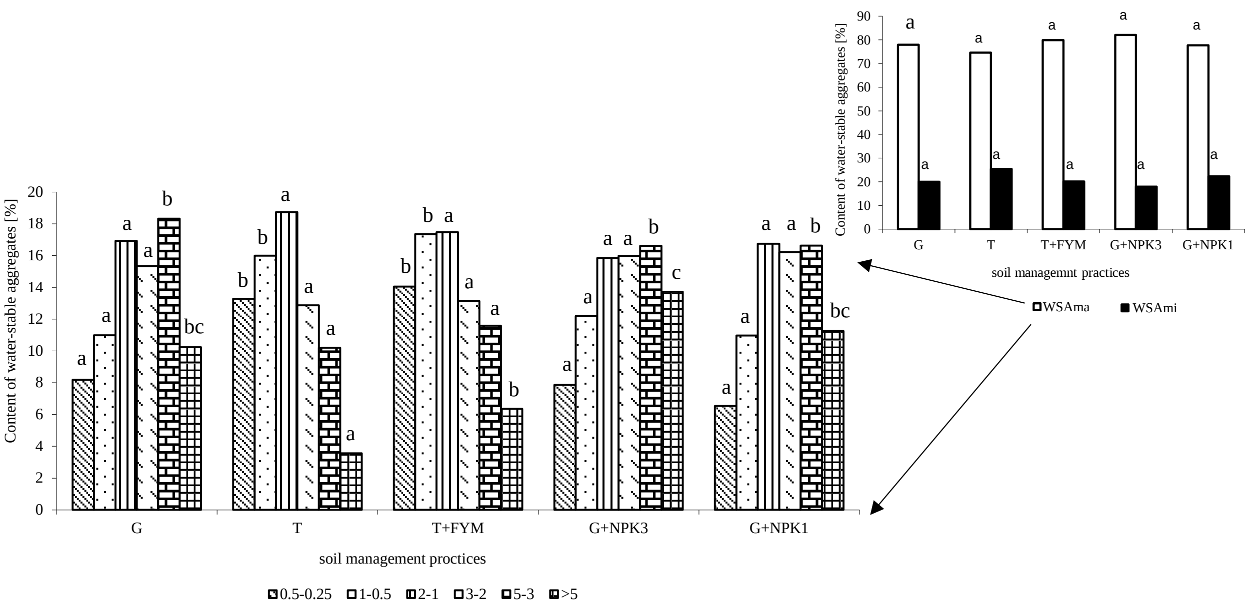

Figure 1. Statistical evaluation of water-stable aggregates contents under different soil-management practices

where: G – control; T – tillage; T+FYM – tillage+farmyard manure; G+NPK3 – doses of NPK fertilisers in 3-rd intensity for vineyards; G+NPK1 – doses of NPK fertilisers in 1st intensity for vineyards; WSA_{ma} – water-stable macro-aggregates; WSA_{mi} – water-stable micro-aggergates.
Different letters between columns (a, b, c) indicate that treatment means are significantly different at $P < 0.05$ according to *LSD* multiple-range test.

crease of 90, 82, 81, 148 and 130% of SOC in these size fractions of WSA_{ma} over the period of 8 years. As mentioned above, C in the soil is reduced due to cultivation. However, its content in the size fractions of WSA_{ma} was increased, which means that part of C after the soil disturbances is sequestered inside of the WSA_{ma}, especially in the two smallest size fractions (1–0.5 and 0.5–0.25 mm). There was not found to be any significant effect on the build-up of SOC in the individual aggregate sizes of WSA in the case of the application of NPK in the 1st and 3rd intensities of vineyard fertilisation (Table 3). Fertilisers can influence SOM in a different ways. Their use improves residue quantity and quality. But this does not necessarily increase the SOC pool. Tong *et al.* (2014) reported that the soils under NPK and NP treatments significantly increased SOC stocks. However, fertilisers may also decrease C content

T a b l e 2

Statistical evaluation of organic and labile carbon contents in size fractions of water-stable aggregates

Parameters	Size fractions of water-stable aggregates in mm		Treatments				
			G	T	T+FYM	G+NPK3	G+NPK1
SOC [g /kg]	WSA_{mi}	<0.25	12.2^{b}	10.0^{a}	12.1^{b}	12.6^{b}	12.7^{b}
	WSA_{ma}	0.25–0.5	14.0^{ab}	12.4^{a}	16.0^{b}	15.0^{ab}	15.0^{ab}
		0.5–1	16.8^{ab}	14.5^{a}	18.8^{b}	16.3^{ab}	17.2^{ab}
		1–2	16.4^{a}	15.5^{a}	19.3^{b}	17.2^{ab}	17.4^{ab}
		2–3	14.9^{ab}	14.8^{a}	17.8^{c}	17.4^{bc}	16.3^{abc}
		3–5	14.9^{a}	15.9^{ab}	19.6^{c}	17.7^{bc}	16.7^{ab}
		>5	16.9^{a}	17.5^{a}	23.3^{b}	18.9^{a}	17.1^{a}
	Mean WSA_{ma}		15.7^{a}	15.1^{a}	19.1^{c}	17.1^{b}	16.6^{b}
C_{NL} [g /kg]	WSA_{mi}	<0.25	10.6^{b}	8.37^{a}	10.3^{b}	10.6^{b}	11.0^{b}
	WSA_{ma}	0.25–0.5	12.2^{ab}	10.5^{a}	13.8^{b}	12.9^{ab}	13.0^{ab}
		0.5–1	14.8^{ab}	12.8^{a}	16.3^{b}	13.9^{ab}	14.8^{ab}
		1–2	14.5^{ab}	13.0^{a}	16.6^{b}	15.0^{ab}	15.4^{b}
		2–3	13.2^{ab}	12.8^{a}	15.5^{c}	15.1^{bc}	14.2^{abc}
		3–5	13.0^{a}	13.8	17.1^{b}	15.1^{ab}	14.7^{a}
		>5	14.9^{a}	15.0^{a}	20.1^{b}	16.2^{a}	15.1^{a}
	Mean WSA_{ma}		13.8^{a}	13.0^{a}	16.6^{c}	14.7^{b}	14.5^{ab}
C_{L} [g /kg]	WSA_{mi}	<0.25	1.57^{a}	1.67^{ab}	1.80^{ab}	2.00^{b}	1.68^{ab}
	WSA_{ma}	0.25–0.5	1.76^{a}	1.93^{ab}	2.42^{b}	2.09^{ab}	2.01^{ab}
		0.5–1	2.08^{a}	1.93^{a}	2.44^{a}	2.42^{a}	2.43^{a}
		1–2	1.91^{a}	2.43^{bc}	2.66^{c}	2.20^{ab}	1.99^{a}
		2–3	1.73^{a}	2.11^{ab}	2.32^{b}	2.23^{b}	2.03^{ab}
		3–5	1.81^{a}	2.17^{ab}	2.56^{b}	2.54^{b}	1.97^{a}
		>5	2.08^{a}	1.93^{a}	2.44^{a}	2.42^{a}	2.43^{a}
	Mean WSA_{ma}		1.90^{a}	2.08^{ab}	2.47^{b}	2.32^{b}	2.14^{ab}

where: SOC – organic carbon in water-stable aggregates; C_{NL} – non-labile carbon in water-stable aggregates; C_{L} – labile carbon in water-stable aggregates; WSA_{mi} – water-stable macro-aggregates; WSA_{mi} – water-stable micro-aggregates; G – control; T – tillage; T+FYM – tillage+farmyard manure; G+NPK3 – doses of NPK fertilisers in 3rd intensity for vineyards; G+NPK1 – doses of NPK fertilisers in 1st intensity for vineyards. Different letters between columns (a, b, c) indicate that treatment means are significantly different at $P < 0.05$ according to *LSD* multiple-range test.

T a b l e 3

Trends of the SOC distribution in the WSA during the 2008–2015 (y = SOC content) with time (x = years)

Treatments	Equations	Probability	Trend
SOC in WSA_{ma} >5 mm			
G	y = 0.0071x + 2.5071	n.s.	increase
T	y = 1.3333x – 2664.5	$^{++}$	increase
T+FYM	y = 1.2929x – 2577.3	n.s.	increase
G + NPK3	y = 0.9298x – 1851.3	n.s.	increase
G + NPK1	y = 0.506x – 1000.6	n.s.	increase
SOC in WSA_{ma} 5–3 mm			
G	y = –0.1143x + 244.74	n.s.	decrease
T	y = 1.175x – 2347.6	$^{+}$	increase
T+FYM	y = 0.9774x – 1946.4	$^{+}$	increase
G + NPK3	y = 0.2643x – 513.94	n.s.	increase
G + NPK1	y = –0.5917x + 1206.8	n.s.	decrease
SOC in WSA_{ma} 3–2 mm			
G	y = –0.275x + 568.1	n.s.	decrease
T	y = 0.9298x – 1855.3	n.s.	increase
T+FYM	y = 0.6762x – 1342.4	$^{+}$	increase
G + NPK3	y = 0.1964x – 377.75	n.s.	increase
G + NPK1	y = –0.456x + 933.4	n.s.	decrease
SOC in WSA_{ma} 2–1 mm			
G	y = 0.0536x – 91.346	n.s.	increase
T	y = 0.9738x – 1943.4	$^{+}$	increase
T+FYM	y = 0.8905x – 1771.9	n.s.	increase
G + NPK3	y = 0.0321x – 47.468	n.s.	increase
G + NPK1	y = –0.2536x + 527.47	n.s.	decrease
SOC in WSA_{ma} 1–0.5 mm			
G	y = 0.056x – 95.786	n.s.	increase
T	y = 1.2167x – 2432.8	$^{+}$	increase
T+FYM	y = 0.9083x – 1808.3	n.s.	increase
G + NPK3	y = –0.2238x + 466.49	n.s.	decrease
G + NPK1	y = 0.9369x – 1867.4	n.s.	increase
SOC in WSA_{ma} 0.5–0.25 mm			
G	y = –0.5381x + 1096.4	n.s.	decrease
T	y = 0.775x – 1546.5	$^{+}$	increase
T+FYM	y = 0.394x – 776.61	n.s.	increase
G + NPK3	y = –0.6095x + 1241	n.s.	decrease
G + NPK1	y = 0.3405x + 699.87	n.s.	decrease
SOC in WSA_{mi} <0.25 mm			
G	y = –0.1488x + 311.52	n.s.	decrease
T	y = 0.4155x – 825.69	n.s.	increase
T+FYM	y = 0.1488x – 287.19	n.s.	increase
G + NPK3	y = 0.3762x – 744.11	n.s.	increase
G + NPK1	y = 0.0881x – 164.55	n.s.	increase

where: G – control; FYM – farmyard manure; G + NPK3 – doses of NPK fertilisers in 3rd intensity for vineyards; G + NPK1 – doses of NPK fertilisers in 1st intensity for vineyards; SOC – soil organic carbon content; WSA_{ma} – water-stable macroaggregates, WSA_{mi} – water-stable micro aggregates. $^{++}P \leq 0.01$; $^{+}P \leq 0.05$; n.s. – non-significant.

T a b l e 4

Trends in the C_{NL} distribution in the WSA during the 2008–2015 (y = C_{NL} content) with time (x = years)

Treatments	Equations	Probability	Trend
C_{NL} in WSA_{ma} >5 mm			
G	y = 44.917x – 75412	n.s.	increase
T	y = 1085.5x – 2E+06	$^{+}$	increase
T+FYM	y = 1133.5x – 2E+06	n.s.	increase
G + NPK3	y = 736.01x – 1E+06	n.s.	increase
G + NPK1	y = 489.43x – 969377	n.s.	increase
C_{NL} in WSA_{ma} 5–3 mm			
G	y = –50.5x + 114625	n.s.	decrease
T	y = 981.35x – 2E+06	$^{+}$	increase
T+FYM	y = 921.99x – 2E+06	$^{+}$	increase
G + NPK3	y = 225x – 437456	n.s.	increase
G + NPK1	y = –500.77x + 1E+06	n.s.	decrease
C_{NL} in WSA_{ma} 3–2 mm			
G	y = –196.46x + 408392	n.s.	decrease
T	y = 751.01x – 1E+06	n.s.	increase
T+FYM	y = 636.33x – 1E+06	$^{++}$	increase
G + NPK3	y = 174.69x – 336253	n.s.	increase
G + NPK1	y = –453.45x + 926357	n.s.	decrease
C_{NL} in WSA_{ma} 2–1 mm			
G	y = 77.429x – 141240	n.s.	increase
T	y = 862.48x – 2E+06	$^{+}$	increase
T+FYM	y = 739.76x – 1E+06	n.s.	increase
G + NPK3	y = 16.167x – 17530	n.s.	increase
G + NPK1	y = –203.48x + 424716	n.s.	decrease
C_{NL} in WSA_{ma} 1–0.5 mm			
G	y = 72.071x – 130292	n.s.	increase
T	y = 1199.1x – 2E+06	$^{+}$	increase
T+FYM	y = 912.48x – 2E+06	n.s.	increase
G + NPK3	y = –223.36x + 463164	n.s.	decrease
G + NPK1	y = 874.26x – 2E+06	n.s.	increase
C_{NL} in WSA_{ma} 0.5–0.25 mm			
G	y = -424.3x + 865686	n.s.	decrease
T	y = 750.8x – 1E+06	$^{+}$	increase
T+FYM	y = 301.56x – 592793	n.s.	increase
G + NPK3	y = –536.06x + 1E+06	n.s.	decrease
G + NPK1	y = –272.33x + 560788	n.s.	decrease
C_{NL} in WSA_{mi} <0.25 mm			
G	y = 1.5714x + 7461	n.s.	increase
T	y = 433.73x – 864069	n.s.	increase
T+FYM	y = 193x – 377881	n.s.	increase
G + NPK3	y = 443.81x – 882121	n.s.	increase
G + NPK1	y = 159.65x – 310174	n.s.	increase

where: G – control; FYM – farmyard manure; G + NPK3 – doses of NPK fertilisers in 3rd intensity for vineyards; G + NPK1 – doses of NPK fertilisers in 1st intensity for vineyards; C_{NL} – non-labile carbon content; WSA_{ma} – water-stable macroaggregates, WSA_{mi} – water-stable micro aggregates. $^{++}P \leq 0.01$; $^{+}P \leq 0.05$; n.s. – non-significant.

T a b l e 5

Trends of C_L distribution in the WSA during the 2008–2015 (y = C_L content) with time (x = years)

Treatments	Equations	Probability	Trend
C_L in WSA_{ma} >5 mm			
G	y = –37.774x + 77919	n.s.	decrease
T	y = 230.01x – 460149	n.s.	increase
T+FYM	y = 159.33x – 317307	n.s.	increase
G + NPK3	y = 193.75x – 387052	n.s.	increase
G + NPK1	y = 15.571x – 29333	n.s.	increase
C_L in WSA_{ma} 5–3 mm			
G	y = –63.744x + 130027	n.s.	decrease
T	y = 193.65x – 387369	++	increase
T+FYM	y = 55.393x – 108862	n.s.	increase
G + NPK3	y = 39.327x – 76564	n.s.	increase
G + NPK1	y = -90.893x + 184796	n.s.	decrease
C_L in WSA_{ma} 3–2 mm			
G	y = –78.494x + 159624	n.s.	decrease
T	y = 177.32x – 354572	n.s.	increase
T+FYM	y = 39.905x – 77946	n.s.	increase
G + NPK3	y = 21.78x – 41584	n.s.	increase
G + NPK1	y = –2.5x + 7054	n.s.	decrease
C_L in WSA_{ma} 2–1 mm			
G	y = –23.815x + 49810	n.s.	decrease
T	y = 111.33x – 221516	+	increase
T+FYM	y = 150.71x – 300501	n.s.	increase
G + NPK3	y = 15.976x – 29938	n.s.	increase
G + NPK1	y = –50.054x + 102672	n.s.	decrease
C_L in WSA_{ma} 1–0.5 mm			
G	y = –16.077x + 34423	n.s.	decrease
T	y = –7.9762x + 17974	n.s.	decrease
T+FYM	y = –4.1429x + 10769	n.s.	decrease
G + NPK3	y = –0.4107x + 3245,1	n.s.	decrease
G + NPK1	y = 62.66x – 123608	n.s.	increase
C_L in WSA_{ma} 0.5–0.25 mm			
G	y = –113.76x + 230584	n.s.	decrease
T	y = 24.202x – 46758	n.s.	increase
T+FYM	y = 111.54x – 221936	n.s.	increase
G + NPK3	y = –73.423x + 149775	n.s.	decrease
G + NPK1	y = –68.101x + 138996	n.s.	decrease
C_L in WSA_{mi}			
G	y = –150.38x + 304056	+	decrease
T	y = –18.25x + 38377	n.s.	decrease
T+FYM	y = –44.19x + 90688	n.s.	decrease
G + NPK3	y = –67.619x + 138014	n.s.	decrease
G + NPK1	y = –71.56x + 145621	n.s.	decrease

where: G – control; FYM – farmyard manure; G + NPK3 – doses of NPK fertilisers in 3rd intensity for vineyards; G + NPK1 – doses of NPK fertilisers in 1st intensity for vineyards; C_L – labile carbon content; WSA_{ma} – water-stable macroaggregates, WSA_{mi} – water-stable micro aggregates. $^{++}P \leq 0.01$; $^{+}P \leq 0.05$; n.s. – non-significant.

as compared to unfertilised soil (Shimizu *et al.* 2009). This indicates C loss which is connected with the higher use of chemical fertilisers – especially nitrogen (Edwards *et al.* 1992; Yang 2011). On the other hand, higher nutrient contents through biomass production can increase SOC in the higher size fractions of WSA_{ma}, especially in the short-term (Šimanský & Polláková 2012). As mentioned above, overall the highest average content of SOC in WSA_{ma} was determined in the T+FYM treatment (Table 2). However, application of FYM (40 t/ha) significantly built-up SOC in WSA_{ma} at an average rate of 0.98 and 0.68 g/kg/y for only the size fractions 5–3 mm and 3–2 mm, respectively (Table 3). Expressed as percentage, this is an increase of 44, and 30% of SOC in these size fractions of WSA_{ma} over the period of 8 years. Results of our study have shown that the highest carbon sequestration after the FYM application is connected with the higher size fractions of WSA_{ma}. Similar results were found in the studies of Kundu *et al.* (2007) and Huang *et al.* (2010). The study of Tong *et al.* (2014) found there to be increased amplitude of stock and sequestration rate in C under FYM, than for mineral fertiliser. Our results confirm this findings (Table 2).

Non-labile carbon in water-stable aggregates

Soil organic-carbon pools can be divided into a labile pool and a recalcitrant fraction (Belay-Tedla *et al.* 2009). Both pools were determined in this study. The content of non-labile carbon (C_{NL}) in WSA, which represents a large sized pool and slow response to soil micro-organism activity, is shown in Table 2. The C_{NL} contents in WSA ranged from 84 to 89% (from SOC) and the effect of soil management practices on C_{NL} in WSA were significant. The C_{NL} contents reflected the contents of SOC in WSA. Overall, the highest average content of C_{NL} in WSA_{ma} was found for the T+FYM treatment, while the lowest ones were in the T treatment. The content of C_{NL} in WSA_{ma} increased on average in the following order: T < G < G+NPK1 < G+NPK3 < T+FYM. The dynamics of C_{NL} at individual aggregate sizes of WSA_{ma} showed that intensive tillage significantly increased C_{NL} in WSA_{ma}. This was especially so in the last two smallest size fractions of WSA_{ma} 1–0.5 and 0.5–0.25 mm, except for the size fraction of 3–2 mm during the whole period (Table 4). The same was found in case of WSA_{mi}. Application of FYM significantly built-up the C_{NL} in WSA_{ma} at an average rate of 0.92 and 0.64 g/kg/y across the size fractions of 5–3 mm and 3–2 mm, respectively. That means increase of 152% and 132% for C_{NL} in WSA_{ma} in 5–3 mm and 3–2 mm over the period. The values of C_{NL} after the application of mineral fertilisers (G+NPK1 a G+NPK3) had great fluctuations during the individual years (2008–2015) and therefore it was not possible to estimate the trend in the change of their values for the individual aggregate size fractions.

Labile carbon in water-stable aggregates

Tillage had no significant effect on the C_L content in WSA_{mi} and the average content of WSA_{ma} (Table 2). However, when evaluating the C_L at different aggregate sizes of WSA_{ma}, there was found to be a significant difference in the C_L content in WSA_{ma} 1–2 mm between T, G and G+NPK1 treatments. In the T treatment, the average content of C_L in WSA_{mi} and C_L in WSA_{ma} was 1.67 g/kg and 2.08 g/kg, respectively (Table 2). The trend line in Table 5 shows that the C_L increase rate in the cultivated treatment ranged from 24 mg/kg/y (WSA_{ma} 0.5–0.25 mm) to 230 mg/kg/y (WSA_{ma} >5 mm). However there was found to be a significant increase of C_L content only in the size fractions of 5–3 mm and 2–1 mm over the period.

The T+FYM treatment was found to have the highest C_L in all individual size fractions of WSA_{ma} (Table 2). The results are consistent with the findings of Purakayastha *et al.* (2008) and Abdollahi *et al.* (2014), where the application of FYM increased the labile C content. Application of FYM decreased C_L in WSA at an average rate of –4 and –44 mg/kg/y in the size fractions of 1–0.5 mm and <0.25 mm, respectively. However there was no statistical significance (Table 5). The built up of C_L in the WSA showed great fluctuations, which was caused by the timing of the FYM application. Overall, the highest C_L content was, however found in the size fraction of WSA_{ma} 2–1 mm, which is in line with the study of Abdollahi *et al.* (2014). Also Degens (1997) found higher C_L contents in the aggregate size of >1 mm. Zhang & Peng (2006) reported an increase of C_L in WSA >5 mm due to FYM application. This is an aggregation effect which creates the space for sequestration of higher C_L contents as found in our study (Table 5).

There were significant differences between the G and G+NPK3 treatments in the C_L in WSA_{mi} and average content of C_L in WSA_{ma}. Generally, the application of higher NPK doses resulted in higher contents of C_L in WSA_{ma} and in WSA_{mi}, as compared to the lower doses of mineral fertiliser (Table 2). The dynamics of the C_L in WSA were influenced by the different NPK doses in the vineyard during the 2008–2015 (Table 5). Application of NPK at the 3rd intensity of fertilisation builds up C_L in WSA at an average rate of 193, 39, 21 and 15 mg/kg/y across the size fractions of > 5 mm, 5–3 mm, 3–2 mm and 2–1 mm, respectively. Again however, there was no statistical significance. With the NPK treatment we observed a decline of C_L in WSA at an average rate of –0.4, –73 and –67 mg/kg/y across the size fractions of 1–0.5 mm, 0.5–0.25 mm and <0.25 mm, respectively, but again with no statistical significance. Our data also showed that in G+NPK1 the most intensive increase of C_L in WSA_{ma} in the size fraction of 1–0.5 mm (63 mg/kg/y). The greatest decline was in the size fraction of 5–3 mm (–91 mg/kg/y) (Table 5). Conteh *et al.* (1999) reported that C_L in the soil is related to the contents of fulvic acids, soil polysaccharides and soil microbial biomass carbon. Variable rhizodeposition, a major source of labile carbon in the soil during the year, as well as microbial activity, cause the fluctuation of C_L production in the soil. This will be influenced by fertilisation (Šimanský 2013). Hence, microbial communities of decomposers in the soil can prefer labile fractions of organic matter as a carbon source. This is positively reflected in aggregation (Shepherd *et al.* 2001) and might result in a better physical protection also of the labile C inside the aggregates (Peth *et al.* 2008).

CONCLUSION

Our study emphasizes the importance of soil-management practices in relation to carbon sequestration, mainly in water-stable aggregates, for a commercial vineyard. Water-stable aggregates are able to protect carbon. So in this regard it is necessary to pay further attention to their stability, especially in relation of intensive cultivation of vineyards. Water-stable micro-aggregates might be responsible for carbon sequestration in the intensive tilled and fertilised vineyard soils. The results of our study indicate that the application of farmyard manure increases the contents of soil organic carbon and both its labile and non-labile forms in water-stable aggregates. Significant differences in the dynamics of carbon in water-stable aggregates indicate the merit of their use as a sensitive indicator of the quality of the soil environment under the different soil management practices. This information is very important for winegrowers. Because on this basis, they can optimize soil-management practices, and avoid environmental degradation of their soils. Based on our findings, we recommend a decrease in the application of high doses of NPK in 3rd intensity of fertilisation for vineyards which means low than 125 kg/ha N, 50 kg/ha P and 185 k/ha K, as well as less intensive vineyard soils cultivation. Application of farmyard manure at rate of 40 t/ha in 3–4 yearly cycles and lower amounts of mineral fertilisers than 100 kg/ha N, 30 kg/ha P and 120 k/ha K (1st intensity of fertilisation for vineyards) would be more suitable for sustainable management with respect to carbon sequestration.

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