INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2024, 38, 311-324
doi: 10.31545/intagr/188617

Luvisol soil macroaggregates under the influence of conventional, strip-till, and reduced tillage practice

Piotr P. Wojewódzki[1], Krystyna Kondratowicz-Maciejewska[1], Bożena Dębska[1], Iwona Jaskulska[2], Dariusz Jaskulski[2], Jarosław Pakuła[1]*

[1]Department of Biogeochemistry and Soil Science, Bydgoszcz University of Science and Technology in Bydgoszcz, Bernardyńska 6/8, 85-029 Bydgoszcz, Poland
[2]Department of Agronomy, Bydgoszcz University of Science and Technology in Bydgoszcz, Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland

Received February 14, 2024; accepted May 13, 2024

A b s t r a c t. The study evaluated the influence of the tillage system no-till (RT), strip-till (ST-OP), conventional till on the stability and distribution of soil aggregates as well as the relationship between the size-classes of soil aggregates and the content and quality of organic matter. The soil was sampled in a field experiment from the depth of 0-10 and 10-20 cm. The analyses concerned determination of carbon and nitrogen content, humus fractions, and soil aggregate size distribution. The obtained fractions of aggregates were analyzed for total organic carbon and total nitrogen content and stability. The results demonstrated that, regardless of the cultivation method, the contribution of particular size-classes of aggregates in the analyzed Luvisol was similar – large macroaggregates (>2 mm) 43-49%, small macroaggregates (2-0.75 mm) 7-8%, and the fraction <0.75 mm 44-49%. The soil aggregates from the 0-10 cm layer of ST-OP and RT were characterized by higher total organic carbon content in comparison to conventional till. Reduced tillage is beneficial for creating more stable structures of soil aggregates, especially in the top soil layer. The stability of soil aggregates positively correlate with total organic carbon content in the soil and parameters describing soil fertility, organic matter stability, and carbon sequestration.

K e y w o r d s: stability, organic matter, tillage system, humic and fulvic acids, soil aggregates

1. INTRODUCTION

One of the important purposes of sustainable agricul-ture is soil quality conservation. Hence, conservation management is fundamental for maintaining and enhancing agricultural production and soil quality (Da Silva Rodrigues Pinto *et al*., 2022). Bronick and Lal (2005) indicate that transition from conventional tillage to no-tillage practices may improve soil quality, which may be proved by some indicators like soil aggregation and soil organic matter (SOM) content. Soil structure is influenced by aggregation, which develops soil physical properties and, consequently, impacts soil fertility and carbon sequestration (Cao *et al*., 2016; Chen *et al*., 2009; 2015; Zhao *et al*., 2017).

Soil structure is a crucial attribute that maintains the conditions of the soil ecosystem and its ability to support biodiversity (Bronick and Lal, 2005). It is primarily created by the contribution of soil aggregates. The main size-classes of soil aggregates are described as macro- and microaggregates. The diameter of macroaggregates ranges from 0.25 to 10 mm, while the diameter of microaggregates is less than 0.25 mm (Niewczas, 2003). A more specified classification indicates the following classes: large macroaggregates (>2000 µm), small macroaggregates (2000-250 µm), microaggregates (250-53 µm), and the silt+clay fraction (<53 µm) (Cambardella and Elliott, 1993).

The factor describing the quality of soil aggregates is the so-called "stability". This term means the resistance of soil aggregates against disruption in water conditions. It is described by various indexes: mean weight diameter (*MWD*), water stable aggregates (WSA), soil aggregate stability (*SAS*), or aggregate stability index (ASI). The WSA, *SAS*, and ASI indexes are expressed in % and indicate

*Corresponding author e-mail: piotr.wojewodzki@pbs.edu.pl

the contribution of water resistant soil aggregates. Soil aggregate structure and aggregate stability are important factors that contribute to sustainable soil quality and soil erosion potential (Williams and Petticrew, 2009); hence, the stability can be used as an indicator of soil structure (Mikha *et al*., 2024; Six *et al*., 2000). The stability and size distribution of soil aggregates are developed by various mechanisms. In general, these parameters positively correlate with the content of soil organic matter, clay minerals, and multivalent cations and their complex in soil aggregates (Zhao *et al*., 2017). A positive relationship between soil aggregate stability, the content of humic substances, and cation exchange capacity has been revealed (Bartlová *et al*., 2015; Lützow *et al*., 2006; Oades, 1984; Six *et al*., 2002). An important factor affecting the stability and size distribution of soil aggregates is also land use, tillage practices, and fertilization (Bronick and Lal, 2005; Khan *et al*., 2022; Tobiašová, 2011; Yang *et al*., 2023; Zhao *et al*., 2017, 2023).

The study conducted by Al-Kaisi *et al*. (2014) on five tillage systems indicated that the stability of micro- and macroaggregates was the highest for no-till practices and the lowest for deep rip system as follows: no-till > strip-till>chisel plow>moldboard plow>deep rip. This research also revealed a positive correlation between the content of soil organic carbon (SOC) and aggregate stability as well as a decrease in SOC and total nitrogen (TN) content when comparing no-till and strip-till practices with plow practices. On the basis of a 34-year field experiment, Yang *et al*. (2023) concluded that fertilization including manure contributed to better improvement in soil organic carbon, total nitrogen, particle organic carbon, and microbial biomass carbon in all aggregates than the fertilizer alone. The study also revealed that SOC in different aggregates increased with the increased aggregate size and that the contribution rate of SOC and TN in macroaggregates was positively associated with the aggregate stability and size-class. The work by Wang *et al*. (2019) on the influence of tillage treatments on the distribution of soil aggregates and organic carbon content indicated that no-tillage and reduced tillage practices significantly increased the amount of small macroaggregates in comparison to conventional tillage. It was also noted that the no-tillage treatment significantly increased the organic carbon contents in the upper 10 cm soil layer in the large macroaggregates and microaggregates. In all the analyzed treatments, the share of individual fractions of aggregates was as follows: microaggregates 48-82%, small macroaggregates 5-40%, the silt+clay fraction 9-13%, large macroaggregates 0-10%.

Wu *et al*. (2019) concluded that conservation tillage practices led to changes in the SOC content and the aggregate characteristics of soils. Especially no tillage practices with straw retention enhanced the contents of SOC and TN in the soil macroaggregates.

Improvement of the stability of soil aggregates in agroecosystems depends on the quality of organic matter and its ability to produce humic substances. Humic substances are compounds that are resistant to decomposition and substantially determine the aggregate structure (Volikov *et al*., 2016). The factors influencing soil organic matter (SOM) content and its quality are fertilization, quantity and quality of post-harvest residues (crop rotation), and the tillage system (plow, plowless, strip-till) (Chantigny, 2003; Debska *et al*., 2022, 2020; Dębska *et al*., 2016; Domingo-Olivé *et al*., 2016; Gautam *et al*., 2022; Kalbitz *et al*., 2000; Wang *et al*., 2015; Zhang *et al*., 2019). Some authors (Jaskulska *et al*., 2020; Kassam *et al*., 2019; Li *et al*., 2023; Morris *et al*., 2010; Reicosky, 2015; Wittwer *et al*., 2021) indicate that limiting plow cultivation of soil is one of the key factors reducing the risk of an adverse impact of field crop production on the environment. An example of a far-reaching reduction of tillage treatments is strip-till cultivation. Its essence is deep cultivation of strips of soil for plant growth and an unscattered zone between the rows covered with plant residues. Strip-till and no-till systems are increasingly being promoted because they lead to carbon sequestration, especially in the topsoil (Debska *et al*., 2020; Laufer *et al*., 2016; Six *et al*., 1999). Moreover, as reported by Debska *et al*. (2020), the use of strip-till may increase the share of the carbon fraction of fulvic and humic acids in soil.

The aim of the undertaken research was to investigate the influence of the tillage system (no-till, strip-till, conventional till) on the stability and distribution of soil aggregates and to determine the relationship between the size-classes of soil aggregates and the content and quality of organic matter in soil.

2. MATERIALS AND METHODS

2.1. Study site

The soil was sampled from an experimental field with an area of 16.5 ha at the Research and Development Center in Śmielin (53°09′04.0″ N; 17°29′10.7″ E; 93.8 m above sea level) in the Kuyavian-Pomeranian Voivodeship (Poland). In this area, since 2012, three soil tillage methods have been compared in field experiments: conventional plow tillage (CT), reduced, non-plowing tillage (RT), and strip-till one-pass (ST-OP). The study site and field experiments were described in detail in a previous work (Jaskulska *et al*., 2020). The study area lies in a humid continental climate zone characterized by DFB areas (Peel *et al*., 2007). The mean temperature and rainfall level of the study site are presented in Fig. 1. The assessed soil is Luvisol, characterized by the mean content of sand (2-0.05 mm), silt (0.05-0.002 mm), and clay (<0.002 mm) particles as follows: 48.4, 46.3, and 5.3%. Soil samples were collected

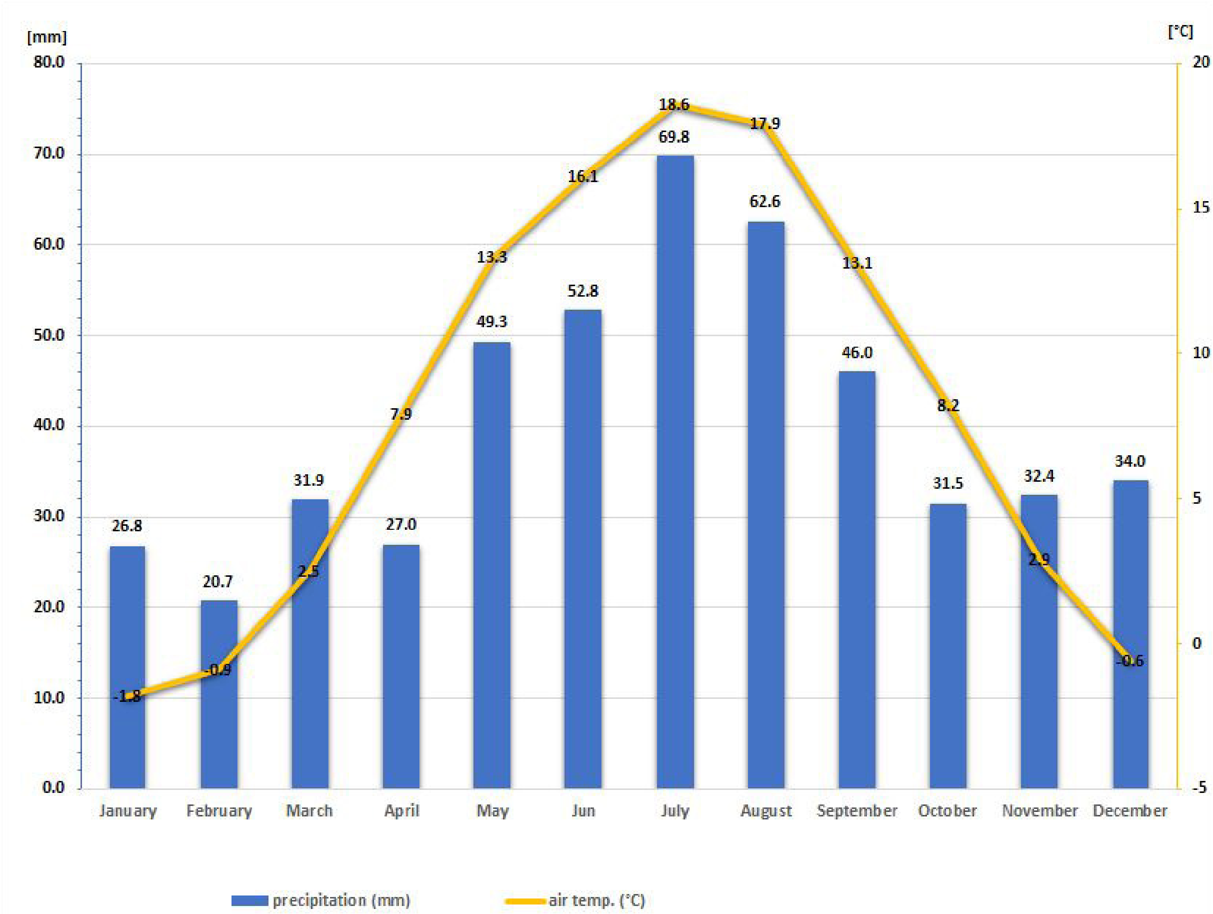

Fig. 1. Mean air temperature and precipitation in the study area (data from the meteorological observation sequence 1981-2010).

after nine years of cropping in the second half of October 2021 after the corn harvest from each of the 4 blocks of the experiment from two layers of 0-10 and 10-20 cm.

2.2. Carbon, nitrogen, and humus fractions

In air-dried soil samples and soil aggregates, the content of total organic carbon (TOC) and total nitrogen (TN) was determined with a Vario Max CN analyzer provided by Elementar (Germany). Briefly, the protocol included sample combustion with oxygen dosing, clearing interfering gases, separating into adsorption columns, and final assaying with a thermal conductivity detector.

In the soil samples the fractional composition of humus was assayed based on the carbon and nitrogen fractions determined in the extracts using a Multi N/C 3100 analyzer (Analytik, Jena, Germany) according to the method described by Debska *et al.* (2020).

The assay of the humus fractional composition was performed according to the following procedure:

– decalcification with 0.05 M HCl (1:10 w/v), 24 h – carbon (Cd) and nitrogen (Nd) in solutions after decalcification;

– extraction of the remaining solid with 0.5 M NaOH (1:50 w/v) with occasional mixing, 24 h, followed by centrifugation, CHAs+CFAs and NHAs+NFAs – sum of the carbon of humic and fulvic acids and sum of the nitrogen of humic and fulvic acids;

– precipitation of humic acids from the resulting alkaline extract with 2 M HCl to pH = 2 and centrifugation – 24 h; CFAs and NFAs – carbon and nitrogen of fulvic acids in solutions.

The C and N content of humic acids (CHAs and NHAs) and carbon and nitrogen of humins (CH and NH) were calculated according to Eqs (1) and (2):

$$\text{C(N)HAs} = \text{C(N)HAs+FAs} - \text{C(N)FAs}, \qquad (1)$$

$$\text{\%C(N)h} = 100\% - \text{\%C(N)HAs} - \text{\%C(N)FAs} - \text{\%C(N)d}. \qquad (2)$$

The fractional composition was expressed in mg kg^{-1} of dry matter of soil sample and as % share of respective fractions in the TOC (TN) pool.

2.3. Analysis of soil aggregates

Air dried samples of soil were sieved to separate five size-classes of macroaggregates: >10, 10-8, 8-5, 5-2, 2-0.75 mm, and the fraction of <0.75 mm. Each aggregate fraction was collected individually. On the ground of each aggregate size-class weight, the aggregate size distribution (*ASD,* %) and the mean weight diameter (*MWD,* mm) were determined using Eq. (3) and Eq. (4):

$$ASD = \frac{m_i}{\sum_{i=1}^{6} m_1} 100, \quad (3)$$

$$MWD = \frac{\sum_{i=1}^{6} m_i d_i}{\sum_{i=1}^{6} m_i}, \quad (4)$$

where: m_i is the mass of aggregate fraction i, and d_i is the mean diameter of the aggregate fraction i (mm).

The obtained fractions of aggregates were analyzed for TOC and TN content and stability. TOC and TN were assayed according to the protocol described in point 2.2. SAS of each macro-aggregate size-class (>10, 10-8, 8-5, 5-2, 2-0.75 mm) was measured in the wet-sieving apparatus (Eijkelkamp 08.13) on 0.25 mm (aggregates <8 mm) and 2.0 mm screens (aggregates >8 mm). The stability of soil aggregates was tested in three replicates of *ca*. 4 g samples. The samples of aggregates were pre-moistened for 10 min before sieving. Then the sieves were placed in the sieve holder of the apparatus over cans with distilled water. Wet sieving was continued for 3 min (1.3 cm stroke, 34 oscillations per minute). Soil particles which passed through the sieve were dried at 105ºC and weighed. The resistant soil material on each sieve was dispersed by 0.1 M tetrasodium pyrophosphate ($Na_4P_2O_7$), dried at 105ºC, and weighed. The stable fraction is equal to the weight of material obtained in the dispersing solution cans (*A*) divided by the sum of weights obtained in the dispersing solution cans and distilled water cans (*B*). The mass of $Na_4P_2O_7$ was subtracted from the weight of dried, dispersed soil material. The soil aggregate stability index (*SAS,* %) was calculated according to Eq. (5):

$$SAS = \frac{A}{A+B} 100. \quad (5)$$

Table 1. Content of total organic carbon and total nitrogen in soil (g kg^{-1})

Tillage system	Layer (cm)	TOC	TN	TOC/TN
		(g kg^{-1})		
CT	0-10	10.41	0.98	10.62
	10-20	10.15	0.97	10.46
ST-OP	0-10	14.49	1.29	11.23
	10-20	10.63	1.02	11.00
RT	0-10	14.81	1.34	11.05
	10-20	10.93	1.03	10.61
I factor tillage system	CT	10.28	0.973	10.51
	ST-OP	12.56	1.16	10.83
	RT	12.89	1.18	10.92
LSD		0.728	0.076	n.s.
II factor layer	0-10	13.23	1.20	11.02
	10-20	10.58	1.01	10.47
LSD		0.346	0.041	n.s.
Interactions				
I/II		0.896	0.098	n.s.
II/I		0.600	0.071	n.s.

2.4. Statistical analyses

The obtained results were assessed by two-way analysis of variance (ANOVA) according to the experimental design of randomized blocks with two experimental factors (soil tillage methods and sampling depth). The values of least significant differences (LSD) were evaluated with the Tukey test at the 0.05 level. The calculations were made using Statistica 13 software (Stat Soft Polska).

3. Results and discussion

3.1. Carbon and nitrogen content and fractional composition of organic matter

The content of TOC and TN in the analyzed soil samples depended on the cultivation method (factor I) and the depth of sampling (factor II) – Table 1. The average TOC content in the soil from the RT and ST-OP plots was significantly higher (~24%) in comparison to CT. Moreover, in the RT and ST-OP variants, a significant TOC difference was noted between layers 0-10 and 10-20 cm. In the 0-10 cm layer, the TOC content was higher by approximately 36% compared to the 10-20 cm layer. The content of TN in the soil was significantly higher (~20%) in RT and ST-OP in comparison with the CT variant. Also, in RT and ST-OP, a significant difference in the TN content was noted between the sampled layers. In the 0-10 cm layer, the TN content was about 28% higher than in the deeper layer (10-20 cm). The TOC and TN content resulted in TOC/TN ratio values ranging from 10.46 to 11.23. Regardless of the tillage system and sampling depth, these differences were not statistically significant. In the RT and ST-OP systems, the TOC/TN ratio was slightly higher in the 0-10 cm layer in comparison to the 10-20 cm layer. The obtained results confirm previous research (Debska *et al*., 2020; Haddaway *et al*., 2017; Si *et al*., 2018; Strickland *et al*., 2015) proving that reduction of cultivation intensity increases the organic carbon content in the soil, especially in its upper layers. Thus, strip-till may be a cultivation method that, like plowless cultivation, leads to carbon sequestration. Some authors (Busari *et al*., 2015; Friedrich *et al*., 2011; Laufer *et al*., 2016; Powlson *et al*., 2012) report that the intensity of sequestration may vary depending on the soil type, rotation, and/or the amount of post-harvest residues.

The content and composition of organic matter is one of the basic factors influencing the physical, chemical, and biological properties of the soil. The humified organic matter in soil, which includes humic acids (HAs), fulvic acids (FAs), and humin (Ch), is considered to be the most microbially stable reservoir of soil organic matter. One of the most important parameters and an indicator of "humus quality" is the ratio of the carbon content of humic acids to the carbon content of fulvic acids (CHAs/CFAs). The values of the CHA/CFA ratio change as the humification process progresses and indicate the potential mobility of organic carbon in the soil (Cao *et al*., 2016; Yang *et al*., 2004). As reported by some authors (Chantigny, 2003; Debska *et al*., 2020; Dębska *et al*., 2016, 2012; Kalbitz *et al*., 2000; Si *et al*., 2018), in agricultural soils, the factor that significantly differentiates the content of humic, fulvic, and humic acid fractions, especially in the top layer of soil, are agrotechnical treatments (rotation, fertilization, systems crops). It is assumed that the CHA/CFA ratio is an indicator of soil fertility. Higher values of this parameter are characteristic of more fertile soils and soils with a higher carbon sequestration index (Hayatu *et al*., 2023).

The fractional composition of organic matter (OM) is presented in Table 2. Generally, the soil from the ST-OP and RT plots, compared to CT, was characterized by higher content of the following fractions: carbon content after decalcification (Cd), carbon content of humic acids (CHAs), and carbon content of fulvic acids (CFAs). In the ST-OP and RT soil, higher content of the analyzed fractions was recorded in the 0-10 cm layer compared to the 10-20 cm fraction. Regardless of the cultivation method, the values of the CHA/CFA ratio were significantly higher in the 0-10 cm layer compared to the 10-20 cm layer. However, there were no significant differences in the value of this ratio between the cultivation systems. This indicates that none of the cultivation methods visibly disturbs the balance of the soil system, which is characteristic in specific habitat conditions (Debska *et al*., 2020). The quality of organic matter and therefore its stability is determined, in addition to the CHA/CFA ratio, by the share of CHAs, CFAs, and CH fractions in the TOC pool. As can be seen from the data presented in Fig. 2a, the shares of the analyzed fractions were generally not determined by the method of cultivation (Factor I). Only the share of CFAs in the RT variant was statistically lower compared to the CT variant. In addition, the share of Cd and CFAs was statistically higher in soil samples taken from the 10-20 cm layer compared to the 0-10 cm layer.

The highest content of nitrogen after decalcification (Nd) was recorded in RT and, regardless of the cultivation system, the soil of the surface layer had higher Nd content compared to the 10-20 cm layer (Table 2). The content of nitrogen of humic acids (NHAs) was the highest in the ST-OP variant, regardless of the sampling depth. The nitrogen content of fulvic acids (NFAs) in variant CT was significantly lower compared to the soil in variant RT. The NHA/NFA ratio values ranged from 1.05 to 1.90 (Table 2). The highest value of this parameter was obtained for the soil from the ST-OP plots. Moreover, higher values were recorded for soil sampled from the surface layer compared to the 10-20 cm layer. The share of NHAs, NFAs, and NH did not differ significantly between the cultivation methods (Fig. 2b). The share of the NHA fraction was higher in soil samples taken from the 0-10 cm layer than from the 10-20 cm layer. An inverse relationship was observed for the share

Table 2. Carbon and nitrogen content (mg kg^{-1}) in humus fractions

Tillage system	Layer (cm)	C_d	C_{HAs}	C_{FAs}	$\frac{C_{HAs}}{C_{FAs}}$	N_d	N_{HAs}	N_{FAs}	$\frac{N_{HAs}}{N_{FAs}}$
CT	0-10	143.8	1877.2	1731.6	1.08	46.5	159.1	120.5	1.34
	10-20	150.8	1728.6	1728.8	1.00	41.0	142.5	135.6	1.05
ST-OP	0-10	182.0	2562.1	2170.0	1.17	34.5	257.7	137.3	1.90
	10-20	158.4	1952.1	1825.6	1.08	23.1	173.1	138.7	1.28
RT	0-10	183.9	2542.3	2091.3	1.21	55.7	182.6	139.2	1.30
	10-20	173.6	2008.6	1823.5	1.10	43.6	155.6	155.2	1.09
I factor tillage system	CT	147.3	1802.9	1730.2	1.04	43.8	150.8	128.0	1.19
	ST-OP	170.2	2257.2	1997.8	1.12	28.8	215.4	138.0	1.59
	RT	178.7	2275.4	1957.4	1.16	49.6	169.1	147.2	1.19
LSD		26.21	274.1	81.2	n.s.	20.2	54.6	17.5	0.42
II factor layer	0-10	169.9	2327.2	1997.6	1.16	45.5	199.8	132.3	1.51
	10-20	160.9	1896.4	1792.6	1.06	35.9	157.0	143.2	1.14
LSD		n.s	208.7	139.3	0.043	4.5	12.5	n.s.	0.14
					Interactions				
I/II		n.s.	n.s.	n.s.	n.s.	n.s.	57.7	n.s.	n.s.
II/I		n.s.	n.s.	n.s.	n.s.	n.s.	12.5	n.s.	n.s.

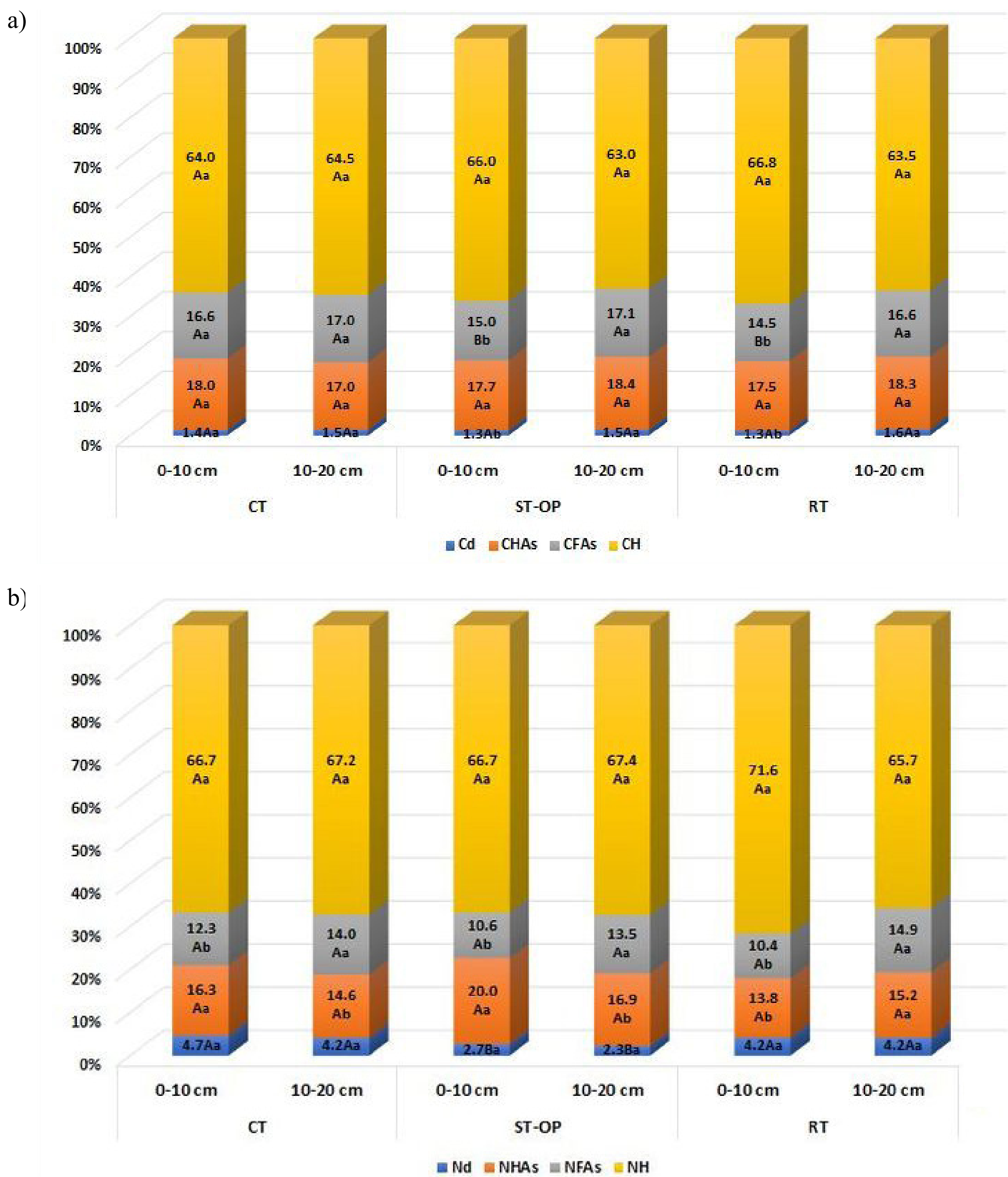

Fig. 2. Carbon (a) and nitrogen (b) share (%) in humus fractions, different capital letters – significant differences for the cultivation methods (CT, ST-OP, RT), different small letters – significant differences for the soil layers (0-10 and 10-20 cm), Cd – carbon content after decalcification, CHAs – carbon content of humic acids, CFAs – carbon content of fulvic acids, CH – humins carbon content, Nd – nitrogen content after decalcification, NHAs – nitrogen content of humic acids, NFAs – nitrogen content of fulvic acids, NH – humins nitrogen content.

of NFAs, *i.e.* a higher share of NFAs was observed in the soil samples from the 10-20 cm layer compared to the 0-20 cm layer.

3.2. Soil aggregate size distribution

The results of the aggregate size distribution indicate no significant differences in the plots within the tillage practices as well as the layer of sampling (Fig. 3). Macroaggregates accounted for the majority of the aggregates (51-56%) in all the tillage treatments in each soil layer. The contribution of large macroaggregates (>2 mm) was in the range of 43-49%, small macroaggregates (2-0.75 mm) ranged from 7 to 8%, and the fraction <0.75 mm accounted for 44-49%. The tillage treatments affected the amount of large macroaggregates in the top layer (0-10 cm), while no differences were observed in the 10-20 cm layer. The amount of large macroaggregates (layer 0-10 cm) was higher in the soil from the ST-OP and RT practices (49 and 48%, respectively) in comparison to the soil from plots under the CT treatments (43%); the differences were not statistically

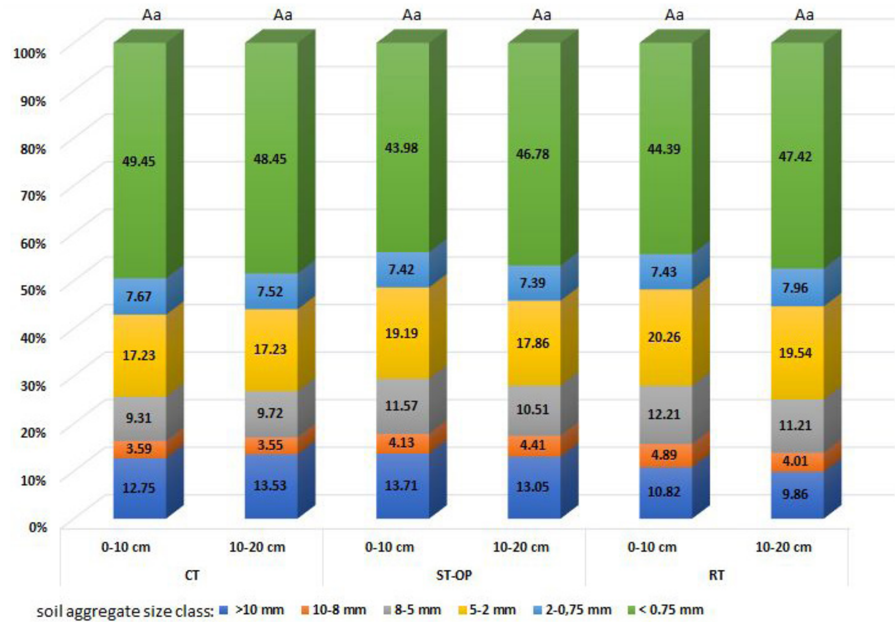

Fig. 3. Soil aggregate size distribution (*ASD*) classes (%), different capital letters – significant differences for the cultivation methods, different small letters – significant differences for the soil layers.

Table 3. Correlation relationships

Parameter	*ASD*						*SAS*				
	>10	10-8	8-5	5-2	2-0.75	<0.75	>10	10-8	8-5	5-2	2-0.75
TOC (g kg^{-1})	0.72	0.59	0.83	0.82	0.79	0.79	0.79	0.66	0.61	0.53	0.43
TN (g kg^{-1})	0.77	0.53	0.86	0.83	0.72	0.83	0.63	0.50	0.48	-	-
TOC/TN	-	-	-	-	0.42	-	0.69	0.65	0.56	0.56	0.54
CHAs (mg kg^{-1})	0.61	-	0.61	0.67	0.67	0.42	0.60	0.67	0.64	0.65	0.60
CFAs (mg kg^{-1})	0.63	0.41	0.65	0.70	0.67	0.67	0.44	0.46	0.45	-	-
CHA/CFAs	-	-	-	-	-	-	0.56	0.61	0.63	0.69	0.74
NHAs (mg kg^{-1})	0.59	-	0.59	-	-	0.47	0.46	0.51	0.52	0.58	0.53
NHA/NFAs					0.49		0.46	0.52	0.56	0.65	0.64

significant. In the 10-20 cm layer, the contribution of large macroaggregates was similar within all the analyzed tillage systems (44-46%).

As shown in the data presented in Table 3, the share of soil aggregates was significantly correlated with the TOC content and the content of humic acid fractions (CHAs, CFAs). These relationships suggest that organic matter is responsible for the size distribution of aggregates. Some authors (Blanco-Canqui and Lal, 2004; Bossuyt *et al*., 2005; Oades and Waters, 1991) indicate that organic matter plays a key role in the formation of microaggregates. These, in turn, combine with each other to form macroaggregates. The contribution of particular size-classes of soil aggregates differ according to the localization of experimental sites. For example, Wang *et al*. (2019) reported that microaggregates were the majority of aggregates (dryland, continental monsoon climate) while on the contrary, other authors noted the highest contribution of large macroaggregates in the soil (Etiophian highland, tropical climate of rainy and dry seasons (Welemariam *et al*., 2018), Brazil, warm tropical climate (Da Silva Rodrigues Pinto *et al*., 2022)).

3.3. TOC and TN in soil aggregates

The TOC content in the aggregates was determined by the cultivation method and depth. Generally, in the 0-10 cm soil layer, the TOC content in each size-class of macroaggregates under ST-OP and RT tillage was higher compared to CT (Table 4). Furthermore, in the variants ST-OP and RT, higher TOC content was noted in the top layer (0-10 cm)

Table 4. TOC content in soil aggregates (g kg^{-1})

Tillage system	Layer (cm)	Aggregate size-class (mm)					
		>10	10-8	8-5	5-2	2-0.75	< 0.75
CT	0-10	11.8	10.5	10.5	11.5	10.9	11.4
	10-20	11.8	13.1	10.4	10.8	11.8	11.3
ST-OP	0-10	14.2	14.4	14.9	15.3	17.2	15.3
	10-20	11.3	10.3	10.9	12.1	11.3	11.1
RT	0-10	14.2	14.4	14.0	14.6	15.7	16.3
	10-20	11.0	10.0	10.1	11.9	12.3	12.0
I factor tillage system	CT	11.7	11.8	10.4	11.1	11.4	11.4
	ST-OP	12.7	12.4	12,9	13.7	14.3	13.2
	RT	12.6	12.2	12.0	13.3	14.0	14.2
LSD		n.s.	n.s.	2.3	2.6	n.s.	n.s.
II factor layer	0-10	13.4	13.1	13.1	13.8	14.6	14.3
	10-20	11.3	11.1	10.5	11.6	11.8	11.5
LSD		1.2	1.6	1.0	0.9	1.4	0.6
		Interactions					
I/II		n.s.	3.6	2.7	n.s.	3.9	3.2
II/I		n.s.	1.6	1.7	n.s.	2.5	1.1

in comparison to the 10-20 cm layer. There was also a significant positive correlation between the carbon content in the aggregates and the overall TOC content in the soil (Table 5). On the ground of the contribution of individual aggregate size-classes and their TOC content, the share of carbon of each aggregate size-class was calculated. According to the data presented in Fig. 4, the highest TOC content was found in the fraction <0.75 mm (45.86-52.09%) and the lowest share was noted in the 10-8 mm soil macroaggregate fraction (4.09-4.84%). Aggregates 5-2 mm contained from 16.29 to 19.48% TOC, fraction 8-5 mm contained from 8.77 to 10.79% TOC, and fraction 2-0.75 mm had from 7.45 to 8.93% TOC. The TOC share in the six considered fractions (>10, 10-8, 8-5, 5-2, 2-0.75, <0.75 mm) was closely related to the contribution of the aggregate size-classes, which was confirmed by significantly positive correlations amounting to 0.865, 0.673, 0.856, 0.827, 0.677, and 0.936, respectively. No significant correlations were obtained between the share of TOC and the TOC content in the aggregates, which is a consequence of the similar TOC content in the particular aggregate size-classes (Table 3). The lack of differences in

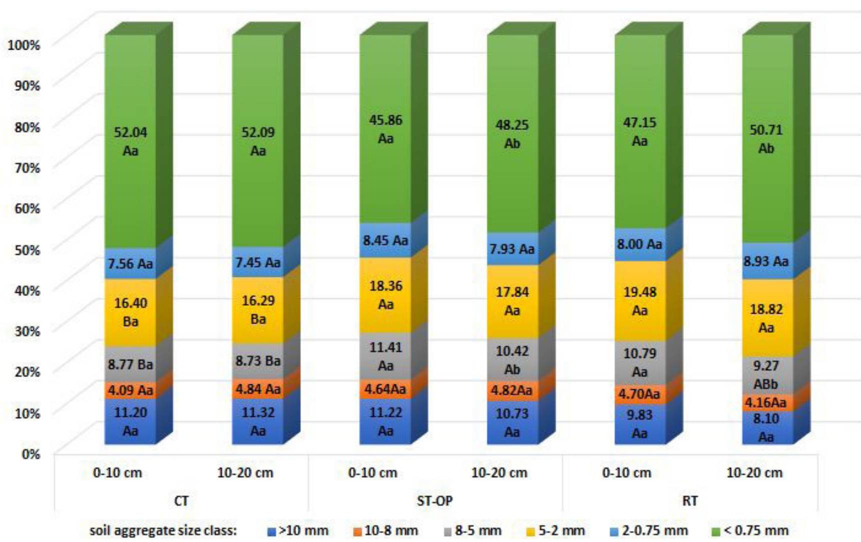

Fig. 4. TOC share in soil aggregates (%), different capital letters – significant differences for the cultivation methods (factor I: CT, ST-OP, RT), different small letters – significant differences for the soil layers (factor II: 0-10 and 10-20 cm), interactions between experimental factors: fraction <0.75: I/II 6.05, II/I 1.64; fraction 10-8 mm II/I 0.56, other interactions – unsignificant.

Table 5. TN content in soil aggregates (g kg^{-1})

Tillage system	Layer (cm)	Aggregate size-class (mm)					
		> 10	10-8	8-5	5-2	2-0.75	< 0.75
CT	0-10	1.11	1.08	1.03	1.02	1.02	1.00
	10-20	0.94	1.14	0.99	0.98	1.07	1.00
ST-OP	0-10	1.26	1.43	1.00	1.35	1.52	1.41
	10-20	0.98	1.02	1.06	1.06	1.03	1.02
RT	0-10	1.22	1.24	1.19	1.30	1.38	1.32
	10-20	0.97	0.93	0.95	1.05	1.12	1.06
I factor tillage system	CT	1.02	1.11	1.01	1.00	1.04	1.00
	ST-OP	1.12	1.22	1.03	1.21	1.27	1.22
	RT	1.10	1.08	1.07	1.17	1.25	1.19
LSD		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
II factor layer	0-10	1.20	1.25	1.00	1.22	1.30	1.24
	10-20	0.96	1.03	1.07	1.03	1.07	1.03
LSD		0.13	0.13	n.s.	0.08	0.15	0.07
		Interactions					
I/II		n.s.	0.42	n.s.	0.28	0.40	0.25
II/I		n.s.	0.23	n.s.	0.14	0.26	0.12

the TOC content in the different size-classes of soil aggregates was confirmed by the research conducted by Canalli *et al*. (2020). The authors observed changes in the TOC content only in aggregates sampled from different depths. They did not demonstrate differences in the TOC content between aggregate size-classes which is also indicate in hereby paper.

The TN content in the aggregates is presented in Table 5. The TN content in the largest soil aggregates (>10 mm) did not depend on the cultivation system but was significantly higher in the surface layer compared to the 10-20 cm layer. The TN content in the aggregate fractions 10-8, 5-2, 2-0.75, and <0.75 mm in the ST-OP and RT variants was significantly higher in the 0-10 cm layer compared to the 10-20 cm layer. The TN content in the ST-OP and RT variants in the 0-10 cm layer was significantly higher than in the CT variant. Generally, the TN content in the individual aggregate size-classes was positively correlated with the TN content in the initial samples before separation into aggregates (correlation coefficient values ranged from 0.525 to 0.830). Regardless of the cultivation system, the highest TN content was found in the fraction <0.75 mm (46.90-49.68%) and the lowest in the 8-10 mm aggregates (3.82-4.91%) (Fig. 5). Aggregates 8-5 mm contained from 9.65 to 11.19% TN, fraction 5-2 mm contained from 17.42 to 18.61% of TN, and fraction 2-0.75 mm had from 7.12 to 8.52% TN. The analyzed distribution of TN (analogously to TOC) in the individual aggregate size-classes was closely related to the shares of the aggregates, which was confirmed by the significantly positive correlation relationships, which amounted to 0.947, 0.884, 0.862, 0.640, 0.670, and 0.939. No significant correlations were obtained between the share of TN and the TN content in the aggregates, which is a consequence of the similar TN content in the particular aggregate size-classes (Table 4). The experimental factors: cultivation systems (CT, ST-OP, RT) or the sampling depth (0-10 and 10-20 cm) did not influence significantly the TN share of each analyzed aggregate fraction (Fig. 5). The obtained results of the TOC and TN content in the soil aggregates (their similar content) confirm the results reported by Kholodov *et al*. (2019), who report that the properties of macroaggregates do not differ significantly from each other.

3.4. Soil aggregate stability

Regardless of the experimental factors, a general tendency was observed: the smaller the size-class of soil macroaggregates, the higher their stability (Fig. 6). Similarly, a general relationship was observed: the less intensive the tillage treatments, the higher the stability of all soil macroaggregates in the top soil layer (0-10 cm), which is consistent with the results reported by other authors (Al-Kaisi *et al*., 2014; Bartlová *et al*., 2015; Castro Filho *et al*., 2002). The effect of using different cultivation methods on the stability of macroaggregates was more visible in the 0-10 cm layer than in the 10-20 cm layer. Comparing the cultivation systems, an increase in the stability of soil macroaggregates was noted in the 0-10 cm layer by 27% for ST-OP and 40% for RT, and in the 10-20 cm layer by 1% for ST-OP and 11% for RT in comparison

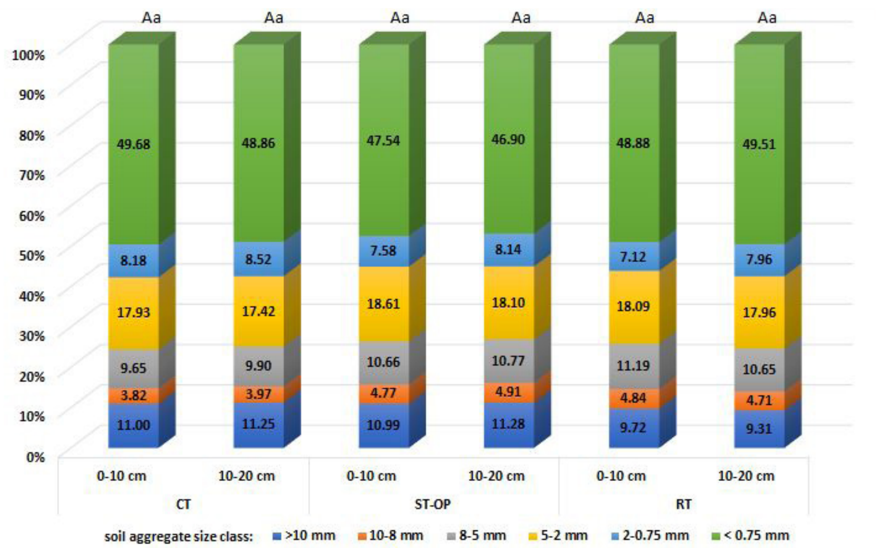

Fig. 5. TN share in soil aggregates (%), different capital letters – significant differences for the cultivation methods (factor I: CT, ST-OP, RT), different small letters – significant differences for the soil layers (factor II: 0-10 and 10-20 cm), no significant interactions between experimental factors.

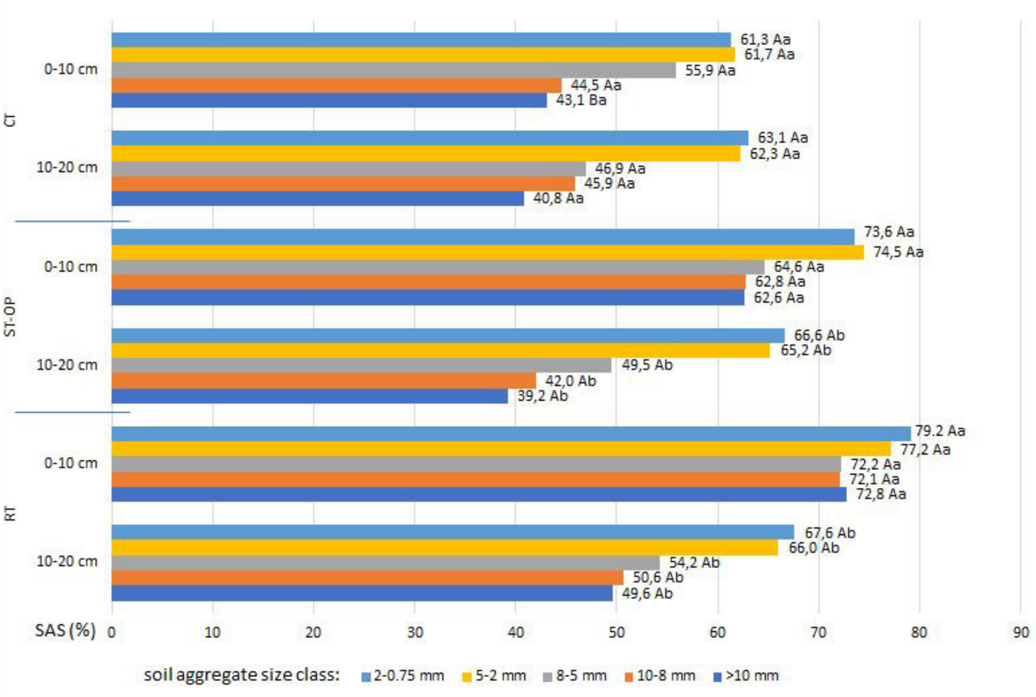

Fig. 6. Soil aggregate stability index *SAS* (%), different capital letters – significant differences for the cultivation methods, different small letters – significant differences for the soil layers.

to CT. The mean SAS of all the macroaggregates was 53.3, 67.6, and 74.7% for CT, ST-OP, an RT in the 0-10 cm layer and 51.8, 52.5, and 57.6%, respectively, in the 10-20 cm layer. The significant effect of the cultivation method concerned only the largest size-class of aggregates (>10 mm) of the top soil layer (0-10 cm). The stability of these aggregates in the ST-OP and RT systems significantly increased in comparison to CT. There was no such effect in the 10-20 cm layer; however, in all the considered macro-aggregate size-classes in the RT an ST-OP systems, there was a SAS significant difference between aggregates from both analyzed soil layers. Furthermore, there was a significant interaction between the experimental factors which affected aggregates >10, 10-8, and 2-0.75 mm.

The other index describing aggregate stability is the mean weigh diameter (MWD). The MWD mean value in the 0-10 cm layer was 3.2, 3.6, and 3.5 for the CT, ST-OP, and RT systems, respectively, and 3.4, 3.4, and 3.2 in the

10-20 cm layer. The differences were not statistically significant. Mikha *et al*. (2024) indicated that aggregate stability and MWD indices are significant metrics of soil structural stability to different degrees, depending on land use and management decisions. This research also confirmed that reducing tillage frequency and intensity resulted in a decrease in soil fragmentation and enhanced the stability of soil aggregates.

The data presented in Table 5 indicate a relationship between the soil aggregate stability index and the quality of organic matter. Regardless of the macroaggregate size-class, SAS positively correlated with the TOC content in the soil, the TOC/TN ratio, content of CHAs and NHAs, and the values of CHA/CFA and NHA/NFA ratios. The SAS of the aggregates >10, 10-8, and 8-5 mm also significantly positively correlated with the carbon content of fulvic acids (CFAs). Martens (2000) and Bipfubusa *et al*. (2008) also observed the relationship between soil aggregate stability and the content of humus fractions – a decrease in the humus fraction content resulted in a decrease in aggregate stability. Řezáčová *et al*. (2021) concluded that this relation is a consequence of the structure of humic substances and primarily the content of aromatic structures therein. The role of aromatic structures in developing the stability of soil aggregates confirmed our results of correlations (Table 5). The content of humic acids as compounds with a more extensive aromatic structure than FAs was correlated with SAS to a greater extent. High (significant) values of SAS correlation coefficients with the CHA/CFA ratio were also obtained. The values of correlation coefficients increased with the decrease in the aggregate size. This indicates that the smaller the aggregate size, the higher the values of the CHA/CFA ratio. The organic matter with higher values of CHAs/CFAs is characteristic for more fertile soils with a higher degree of humification and therefore greater resistance to its decomposition (Dębska *et al*., 2016; Guimarães *et al*., 2013; Yang *et al*., 2004). The obtained relationships indicate that soil with higher values of the CHA/CFA ratio and higher content of humic acid fractions is characterized by higher aggregate stability.

As reported by Zibilske and Bradford (2007) and Williams *et al*. (2016), strip-till creates favorable conditions for plant growth and yield and, at the same time, improves soil quality parameters, as presented in this study.

4. CONCLUSIONS

Regardless of the cultivation method, the contribution of particular size-classes of aggregates in the analyzed Luvisol was similar – large macroaggregates (>2 mm) 43-49%, small macroaggregates (2-0.75 mm) 7-8%, and the fraction <0.75 mm 44-49%. Cultivation systems with reduced tillage promote development of soil macroaggregates.

The content of total organic carbon and total nitrogen in all the analyzed aggregate size-classes was similar and positively correlated with the overall total organic carbon and total nitrogen content in the soil. The aggregates from the 0-10 cm layer of ST-OP and RT systems contained significantly higher total organic carbon content in comparison to the deeper layer (10-20 cm). The soil aggregates from the 0-10 cm layer in the ST-OP and RT variants were characterized by higher total organic carbon content in comparison to the soil aggregates from the conventional tillage system.

Regardless of the experimental factors, a general tendency was observed: the smaller the size-class of soil macroaggregates, the higher their stability. Reduced tillage is beneficial for creating more stable structures of soil aggregates, especially in the top soil layer.

The stability of soil aggregates positively correlated with the total organic carbon content in the soil, humic acid content, and the CHA/CFA ratio, *i.e.* parameters describing soil fertility, organic matter stability, and carbon sequestration.

Conflicts of Interest: The Authors do not declare any conflict of interest.

5. REFERENCES

Al-Kaisi, M.M., Douelle, A., Kwaw-Mensah, D., 2014. Soil microaggregate and macroaggregate decay over time and soil carbon change as influenced by different tillage systems. J. Soil Water Conserv. 69, 574-580. https://doi.org/10.2489/jswc.69.6.574

Bartlová, J., Badalíková, B., Pospíšilová, L., Pokorný, E., Šarapatka, B., 2015. Water stability of soil aggregates in different systems of tillage. Soil Water Res. 10, 147-154. https://doi.org/10.17221/132/2014-SWR

Bipfubusa, M., Angers, D.A., N'Dayegamiye, A., Antoun, H., 2008. Soil aggregation and biochemical properties following the application of fresh and composted organic amendments. Soil Sci. Soc. Am. J. 72, 160-166. https://doi.org/10.2136/sssaj2007.0055

Blanco-Canqui, H., Lal, R., 2004. Mechanisms of Carbon Sequestration in Soil Aggregates. Crit. Rev. Plant Sci. 23, 481-504. https://doi.org/10.1080/07352680490886842

Bossuyt, H., Six, J., Hendrix, P.F., 2005. Protection of soil carbon by microaggregates within earthworm casts. Soil Biol. Biochem. 37, 251-258. https://doi.org/10.1016/j.soilbio.2004.07.035

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3-22. https://doi.org/10.1016/j.geoderma.2004.03.005

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. 3, 119-129. https://doi.org/10.1016/j.iswcr.2015.05.002

Cambardella, C.A., Elliott, E.T., 1993. Carbon and Nitrogen Distribution in Aggregates from Cultivated and Native Grassland Soils. Soil Sci. Soc. Am. J. 57, 1071-1076. https://doi.org/10.2136/sssaj1993.03615995005700040032x

Canalli, L.B.D.S., Santos, J.B.D., Benassi, D.A., Francisco, A.L.O.D., Benassi, C., Aguiar, A.N.D., Cordeiro, E., Mendes, R.S., 2020. Soil Carbon and Structural Quality in Crop Rotations under No-tillage System. Braz. Arch. Biol. Technol. 63, e20190603. https://doi.org/10.1590/1678-4324-solo-2020190603

Cao, Z., Wang, Y., Li, J., Zhang, J., He, N., 2016. Soil organic carbon contents, aggregate stability, and humic acid composition in different alpine grasslands in Qinghai-Tibet Plateau. J. Mt. Sci. 13, 2015-2027. https://doi.org/10.1007/s11629-015-3744-y

Castro Filho, C., Lourenço, A., De F. Guimarães, M., Fonseca, I.C.B., 2002. Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. Soil Till. Res. 65, 45-51. https://doi.org/10.1016/S0167-1987(01)00275-6

Chantigny, M.H., 2003. Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices. Geoderma, Ecological aspects of dissolved organic matter in soils 113, 357-380. https://doi.org/10.1016/S0016-7061(02)00370-1

Chen, H., Hou, R., Gong, Y., Li, H., Fan, M., Kuzyakov, Y., 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil Till. Res. 106, 85-94. https://doi.org/10.1016/j.still.2009.09.009

Cheng, M., Xiang, Y., Xue, Z., An, S., Darboux, F., 2015. Soil aggregation and intra-aggregate carbon fractions in relation to vegetation succession on the Loess Plateau, China. Catena 124, 77-84. https://doi.org/10.1016/j.catena.2014.09.006

Da Silva Rodrigues Pinto, L.A., De Lima, S.S., Da Silva, C.F., Da Mota Gonçalves, R.G., De Sousa Morais, I., Ferreira, R., Da Silva Junior, W.F., Torres, J.L.R., Pereira, M.G., 2022. Soil quality indicators in conventional and conservation tillage systems in the Brazilian Cerrado. Environ. Earth Sci. 81, 306. https://doi.org/10.1007/s12665-022-10426-5

Debska, B., Jaskulska, I., Jaskulski, D., 2020. Method of tillage with the factor determining the quality of organic matter. Agronomy 10, 1250. https://doi.org/10.3390/agronomy10091250

Debska, B., Kotwica, K., Banach-Szott, M., Spychaj-Fabisiak, E., Tobiašová, E., 2022. Soil fertility improvement and carbon sequestration through exogenous organic matter and biostimulant application. Agriculture 12, 1478. https://doi.org/10.3390/agriculture12091478

Dębska, B., Długosz, J., Piotrowska-Długosz, A., Banach-Szott, M., 2016. The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration – results from a field -scale study. J. Soils Sediments 16, 2335-2343. https://doi.org/10.1007/s11368-016-1430-5

Dębska, B., Drąg, M., Tobiasova, E., 2012. Effect of post-harvest residue of maize, rapeseed, and sunflower on humic acids properties in various soils. Pol. J. Environ. Stud. 21.

Domingo-Olivé, F., Bosch-Serra, À.D., Yagüe, M.R., Poch, R.M., Boixadera, J., 2016. Long term application of dairy cattle manure and pig slurry to winter cereals improves soil quality. Nutr. Cycl. Agroecosystems 104, 39-51. https://doi.org/10.1007/s10705-015-9757-7

Friedrich, T., Derpsch, R., Kassam, A., 2011. Global overview of the spread of conservation agriculture. In: Proceedings from the 5th World Congress on Conservation Agriculture, Brisbane, Australia, pp. 26-30.

Gautam, A., Guzman, J., Kovacs, P., Kumar, S., 2022. Manure and inorganic fertilization impacts on soil nutrients, aggregate stability, and organic carbon and nitrogen in different aggregate fractions. Arch. Agron. Soil Sci. 68, 1261-1273. https://doi.org/10.1080/03650340.2021.1887480

Guimarães, D.V., Gonzaga, M.I.S., Da Silva, T.O., Da Silva, T.L., Da Silva Dias, N., Matias, M.I.S., 2013. Soil organic matter pools and carbon fractions in soil under different land uses. Soil Till. Res. 126, 177-182. https://doi.org/10.1016/j.still.2012.07.010

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6, 30. https://doi.org/10.1186/s13750-017-0108-9

Hayatu, N.G., Liu, Y., Han, T., Daba, N.A., Zhang, L., Shen, Z., Li, J., Muazu, H., Lamlom, S.F., Zhang, H., 2023. Carbon sequestration rate, nitrogen use efficiency and rice yield responses to long-term substitution of chemical fertilizer by organic manure in a rice-rice cropping system. J. Integr. Agric. 22, 2848-2864. https://doi.org/10.1016/j.jia.2022.12.006

Jaskulska, I., Romaneckas, K., Jaskulski, D., Wojewódzki, P., 2020. A strip-till one-pass system as a component of conservation agriculture. Agronomy 10, 2015. https://doi.org/10.3390/agronomy10122015

Kalbitz, K., Solinger, S., Park, J.-H., Michalzik, B., Matzner, E., 2000. Controls on the dynamics of dissolved organic matter in soils: A Review. Soil Sci. 165, 277.

Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. Int. J. Environ. Stud. 76, 29-51. https://doi.org/10.1080/00207233.2018.1494927

Khan, F.U., Khan, A.A., Li, K., Xu, X., Adnan, M., Fahad, S., Ahmad, R., Khan, M.A., Nawaz, T., Zaman, F., 2022. Influences of long-term crop cultivation and fertilizer management on soil aggregates stability and fertility in the loess plateau, Northern China. J. Soil Sci. Plant Nutr. 22, 1446-1457. https://doi.org/10.1007/s42729-021-00744-1

Kholodov, V.A., Yaroslavtseva, N.V., Farkhodov, Yu.R., Belobrov, V.P., Yudin, S.A., Aydiev, A.Ya., Lazarev, V.I., Frid, A.S., 2019. Changes in the ratio of aggregate fractions in humus horizons of chernozems in response to the type of their use. Eurasian Soil Sci. 52, 162-170. https://doi.org/10.1134/S1064229319020066

Laufer, D., Loibl, B., Märländer, B., Koch, H.-J., 2016. Soil erosion and surface runoff under strip tillage for sugar beet (*Beta vulgaris* L.) in Central Europe. Soil Till. Res. 162, 1-7. https://doi.org/10.1016/j.still.2016.04.007

Li, K., Hao, Z., Chen, L., Sha, Y., Wang, E., Sui, X., Mi, G., 2023. Conservation strip-till modifies rhizosphere ammonia-oxidizing archaea and bacteria, increases nitrate accumulation and promotes maize growth at grain filling stage. Soil Till. Res. 234, 105821. https://doi.org/10.1016/j.still.2023.105821

Lützow, M.V., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. Eur. J. Soil Sci. 57, 426-445. https://doi.org/10.1111/j.1365-2389.2006.00809.x

Martens, D.A., 2000. Management and crop residue influence soil aggregate stability. J. Environ. Qual. 29, 723-727. https://doi.org/10.2134/jeq2000.00472425002900030006x

Mikha, M.M., Green, T.R., Untiedt, T.J., Hergret, G.W., 2024. Land management affects soil structural stability: Multi-index principal component analyses of treatment interactions. Soil Till. Res. 235, 105890. https://doi.org/10.1016/j.still.2023.105890

Morris, N.L., Miller, P.C.H., J.H.Orson, Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment – A review. Soil Till. Res. 108, 1-15. https://doi.org/10.1016/j.still.2010.03.004

Niewczas, J., 2003. Index of soil aggregates stability as linear function value of transition matrix elements. Soil Till. Res. 70, 121-130. https://doi.org/10.1016/S0167-1987(02)00155-1

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76, 319-337. https://doi.org/10.1007/BF022055990

Oades, J.M., Waters, A.G., 1991. Aggregate hierarchy in soils. Soil Res. 29, 815-828. https://doi.org/10.1071/sr9910815

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633-1644. https://doi.org/10.5194/hess-11-1633-2007

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. Agric. Ecosyst. Environ. 146, 23-33. https://doi.org/10.1016/j.agee.2011.10.004

Reicosky, D.C., 2015. Conservation tillage is not conservation agriculture. J. Soil Water Conserv. 70, 103A-108A. https://doi.org/10.2489/jswc.70.5.103A

Řezáčová, V., Czakó, A., Stehlík, M., Mayerová, M., Šimon, T., Smatanová, M., Madaras, M., 2021. Organic fertilization improves soil aggregation through increases in abundance of eubacteria and products of arbuscular mycorrhizal fungi. Sci. Rep. 11, 12548. https://doi.org/10.1038/s41598-021-91653-x

Si, P., Liu, E., He, W., Sun, Z., Dong, W., Yan, C., Zhang, Y., 2018. Effect of no-tillage with straw mulch and conventional tillage on soil organic carbon pools in Northern China. Arch. Agron. Soil Sci. 64, 398-408. https://doi.org/10.1080/03650340.2017.1359410

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241, 155-176. https://doi.org/10.1023/A:1016125726789

Six, J., Elliott, E.T., Paustian, K., 2000. Soil structure and soil organic matter II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64, 1042-1049. https://doi.org/10.2136/sssaj2000.6431042x

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350-1358. https://doi.org/10.2136/sssaj1999.6351350x

Strickland, T.C., Scully, B.T., Hubbard, R.K., Sullivan, D.G., Abdo, Z., Savabi, M.R., Lee, R.D., Olson, D.M., Hawkins, G.L., 2015. Effect of conservation practices on soil carbon and nitrogen accretion and crop yield in a corn production system in the southeastern coastal plain, United States. J. Soil Water Conserv. 70, 170-181. https://doi.org/10.2489/jswc.70.3.170

Tobiašová, E., 2011. The effect of organic matter on the structure of soils of different land uses. Soil Till. Res. 114, 183-192. https://doi.org/10.1016/j.still.2011.05.003

Volikov, A.B., Kholodov, V.A., Kulikova, N.A., Philippova, O.I., Ponomarenko, S.A., Lasareva, E.V., Parfyonova, A.M., Hatfield, K., Perminova, I.V., 2016. Silanized humic substances act as hydrophobic modifiers of soil separates inducing formation of water-stable aggregates in soils. Catena 137, 229-236. https://doi.org/10.1016/j.catena.2015.09.022

Wang, B., Gao, L., Yu, W., Wei, X., Li, J., Li, S., Song, X., Liang, G., Cai, D., Wu, X., 2019. Distribution of soil aggregates and organic carbon in deep soil under long-term conservation tillage with residual retention in dryland. J. Arid Land 11, 241-254. https://doi.org/10.1007/s40333-019-0094-6

Wang, Y., Hu, N., Xu, M., Li, Z., Lou, Y., Chen, Y., Wu, C., Wang, Z.-L., 2015. 23-year manure and fertilizer application increases soil organic carbon sequestration of a rice-barley cropping system. Biol. Fertil. Soils 51, 583-591. https://doi.org/10.1007/s00374-015-1007-2

Welemariam, M., Kebede, F., Bedadi, B., Birhane, E., 2018. Effect of community-based soil and water conservation practices on soil glomalin, aggregate size distribution, aggregate stability and aggregate-associated organic carbon in northern highlands of Ethiopia. Agric. Food Secur. 7, 42. https://doi.org/10.1186/s40066-018-0193-1

Williams, A., Kane, D.A., Ewing, P.M., Atwood, L.W., Jilling, A., Li, M., Lou, Y., Davis, A.S., Grandy, A.S., Huerd, S.C., Hunter, M.C., Koide, R.T., Mortensen, D.A., Smith, R.G., Snapp, S.S., Spokas, K.A., Yannarell, A.C., Jordan, N.R., 2016. Soil functional zone management: a vehicle for enhancing production and soil ecosystem services in row-crop agroecosystems. Front. Plant Sci. 7. https://doi.org/10.3389/fpls.2016.00065

Williams, N.D., Petticrew, E.L., 2009. Aggregate stability in organically and conventionally farmed soils. Soil Use Manag. 25, 284-292. https://doi.org/10.1111/j.1475-2743.2009.00223.x

Wittwer, R.A., Bender, S.F., Hartman, K., Hydbom, S., Lima, R.A.A., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P.A., Petchey, O., Prechsl, U.E., Schlaeppi, K., Scholten, T., Seitz, S., Six, J., Van Der Heijden, M.G.A., 2021. Organic and conservation agriculture promote ecosystem multifunctionality. Sci. Adv. 7, eabg6995. https://doi.org/10.1126/sciadv.abg6995

Wu, J., Stephen, Y., Cai, L., Zhang, R., Qi, P., Luo, Z., Li, L., Xie, J., Dong, B., 2019. Effects of different tillage and straw retention practices on soil aggregates and carbon and nitrogen sequestration in soils of the northwestern China. J. Arid Land 11, 567-578. https://doi.org/10.1007/s40333-019-0065-y

Yang, C., Sainju, U.M., Li, C., Fu, X., Zhao, F., Wang, J., 2023. Long-term chemical and organic fertilization differently affect soil aggregates and associated carbon and nitrogen in the loess plateau of China. Agronomy 13, 1466. https://doi.org/10.3390/agronomy13061466

Yang, Z.H., Singh, B.R., Sitaula, B.K., 2004. Soil organic carbon fractions under different land uses in Mardi Watershed of Nepal. Commun. Soil Sci. Plant Anal. 35, 615-629. https://doi.org/10.1081/CSS-120030347

Zhang, J., An, T., Chi, F., Wei, D., Zhou, B., Hao, X., Jin, L., Wang, J., 2019. Evolution over years of structural characteristics of humic acids in Black Soil as a function of various fertilization treatments. J. Soils Sediments 19, 1959-1969. https://doi.org/10.1007/s11368-018-2212-z

Zhao, J., Chen, S., Hu, R., Li, Y., 2017. Aggregate stability and size distribution of red soils under different land uses integrally regulated by soil organic matter, and iron and aluminum oxides. Soil Till. Res. 167, 73-79. https://doi.org/10.1016/j.still.2016.11.007

Zhao, S., Yu, F., Zhai, C., Zhong, R., Zhao, Y., Wang, Y., Zhang, J., Meng, Q., 2023. Long-term effects of cattle manure application on the soil aggregate stability of salt-affected soil on the Songnen Plain of North-Eastern China. J. Soils Sediments 23, 344-354. https://doi.org/10.1007/s11368-022-03317-6

Zibilske, L.M., Bradford, J.M., 2007. Soil aggregation, aggregate carbon and nitrogen, and moisture retention induced by conservation tillage. Soil Sci. Soc. Am. J. 71, 793-802. https://doi.org/10.2136/sssaj2006.0217