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Short Communication

Reducing machine movement intensity in the field improves soil structure

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Precision agriculture, which also includes the controlled movement of machines across the field, has several positive economic and environmental aspects. Despite this fact, knowledge gaps were identified, especially regarding the impact of compaction on changes in the humic substances regime and soil structure. For this reason, the first data are presented and discussed in this short communication. Soil samples for the determination of soil organic matter (SOM) content, humic substances (HS), and soil structure parameters were taken from a long-term field experiment of controlled traffic farming. Samples were taken from points along permanent track lines and in places where no machines had passed for 12 years. The study highlights the potential of controlled traffic farming, mainly from point of view improving of soil structure in no-traffic undisturbed parts of agricultural fields. The obtained results also indicate that 12 years of no machinery passing through the field does not significantly affect the parameters of SOM and HS.

Keywords: compaction, soil organic matter, humic substances, soil aggregates

1 Introduction

Mechanized agronomic operations and intensive soil management practices accompanying the intensification of crop production create heavy traffic on arable soils which in turn increases the risk of soil compaction. Soil compaction can also be included among the most significant physical indicators of soil degradation (Gürsoy, 2021). Soil compaction is a process in which the elementary particles get closer to each other and thus significantly affect soil properties. Higher soil compaction reduces total porosity, macro-porosity, and inter-porous connectivity, which results in limited growth of plant roots, a decrease in microbial activity, and in the number of soil organisms (Nawaz et al., 2013). Soil compaction causes a change in soil structure, and an increase in bulk density, which translates into lower soil aeration and water infiltration. Among the internal factors, soil compaction is mainly affected by soil texture, humic substances, and soil water content (Nawaz et al., 2013). Soil compaction is a worldwide environmental problem of increasing importance, occurring in the agricultural sector, especially on arable soils (Nawaz et al., 2013; Gürsoy, 2021) in all developed countries with mechanized agriculture. For example, within the agricultural land fund in the Slovak Republic and the Czech Republic, about 650,000 and 1,500,000 ha are compacted land, which represents almost 30 and 50% of their area.

Many strategies have been used to avoid soil compaction in farmland and improve or alleviate the stresses

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associated with the compacted soil (Gürsoy, 2021). For example, Alskaf et al. (2021) stated that conservation agriculture – a system involving minimal soil disturbance, maintaining a permanent soil cover and diversification of crop species, has the potential to improve soil quality, including the decrease of soil compaction. As stated by Polláková et al. (2021), soil compaction can be reduced by deep reclamation loosening, chiselling, and plowing below the level of the furrow bottom. These are mechanical operations that are carried out to eliminate the problem that has arisen. A much better and less economically demanding solution is to focus on prevention. Both Poláková et al. (2021) and Gürsoy (2021) stated that such a measure is to limit the passage of heavy machinery through the field. Compacted or otherwise degraded soil caused by poor soil management practices reduces the productive and non-productive soil functions. The optimal time for soil regeneration should be as short as possible, but this appears to be a problem. For this reason, burdening the soil as little as possible can be the right strategy to accelerate its regeneration. In this context, the controlled traffic system (CTF) of machines in the field can play an important role in modern, precision agriculture (Rataj et al., 2022). In this short communication, we tried to answer the question: Is 12 years sufficient to improve the structural condition of the soil? We assume that the formation of the soil aggregates will be caused by fragmentation or compaction in the case of tracks after the passage of machines. For uncompacted soil, the tillage system effect will be observed, but it will be significantly smaller than in compacted soil. Soil aggregates will be formed predominantly by the biotic assembly and abiotic separation (H1). These different ways of soil aggregates formation (as a basic unit of soil structure) should be reflected in the soil structure parameters determined in the laboratory (H2). Humic substances will have a significant effect on the formation of the soil structure – more in the case of uncompacted than compacted soil (H3).

2 Material and methods

The studies were performed at the Slovak University of Agriculture farm in Kolinany, 5 km NE of Nitra (48° 22′ 16.97″ N, 18° 12′ 25.43″ E) in the Žitavská upland. The mean annual air temperature was 10.8 °C while the mean annual sum of precipitation was 559 mm (based on the 30-year climatic normal from 1991 to 2020). The soil cover of the experimental field comprises of a Haplic Luvisol (Loamic. Epiclayic. Aric. Cutanic. Hypereutric), Haplic Luvisol (Loamic. Endoclayic. Aric. Colluvic. Cutanic. Hypereutric) and Eutric Reductigleyic Gleysol (Loamic. Aric. Colluvic. Humic) complex (WRB, 2015).

In the 2009/2010 season, a long-term field experiment with the technology of controlled traffic farming was launched. This technology is used on a field of 16 ha. The type of CTF system is 6m OutTrack (64% uncompacted soil, 36% compacted soil). The principle of this technology is to limit the movement of machines in the field to permanent traffic lines only. On grounds of this, it is possible to reduce trafficked field area in the relation to the conventional RTF – random traffic system. In this manner, uncompacted soil (areas without field traffic, since 2010, it is 12 years) and multiple-trafficked soil (permanent tramlines) were created. Commercially available machinery with a standard wheel spacing is used for work operations – as supplied by the manufacturer. The field is cultivated under soil conservation tillage (without plowing) up to a depth of 15 cm. More detailed information is available in other publications (Macak et al., 2017; Rataj et al., 2022).

For this contribution, soil samples were collected in areas characterized by different traffic intensity. One is uncompacted soil – samples marked as "A", and the other is compacted soil – samples marked as "C". Before taking the soil samples, a description of the soil aggregates was carried out (Świtoniak et al., 2018). Subsequently, disturbed soil samples were collected to determine the soil structure, parameters of SOM, and humic substances (HS) in all repetitions of the experiment. Soil samples were taken from two layers, 0–10 cm and 10–20 cm. Standard methods for determining SOM, HS, and soil structure were used (Hrivňaková et al., 2011). The following were determined in the soil samples: content of soil organic carbon (SOC) by sample oxidation in the mixture of $K_2Cr_2O_7$ and H_2SO_4, labile carbon content (C_L) was determined using 0.005 mol/dm^3 $KMnO_4$ by Loginow method, particle-size distribution (pipette method), the group and fractional composition of HS (humic acids – HA, fulvic acids – FA) using the Belchikova and Kononova method, absorbance of HS and HA. On the basis of light absorbance of HS and HA measured at a wavelength of 465 and 650 nm using a Jenway 6400 Spectrophotometer the color quotients of humic substances ($Q^{4/6}_{HS}$) and humic acids ($Q^{4/6}_{HA}$) were calculated. Individual size fractions of soil aggregates were determined by dry sieving (mesh diameters >7, 7–5, 5–3, 3–1, 1–0.5, 0.5–0.25 mm as DSAma – dry sieved macro-aggregates, and <0.25 mm as dry sieved micro-aggregates – DSAmi). These fractions of air-dried aggregates were used to determine water-stable macro- (WSAma) and micro-aggregates (WSAmi) using the Baksheev method. The mean weight diameters (MWD) for both dry sieved aggregates (MWDd) and for water-stable aggregates (MWDw), vulnerability coefficient (Kv), and the stability index of water-stable aggregates (Sw), percentage of aggregate destruction (PAD), and crust index (Ic) were calculated.

All statistical calculations were performed using the STATISTICA data analysis software system, version 13.0 (TIBCO StatSoft Inc, StatSoft Poland, Warsaw). A parametric *T*-test for unpaired two-samples, the Pearson correlation analysis, and PCA (principal component analysis) were used for the evaluation of relationships between SOM, humic substances and soil structure for the compacted and uncompacted soil at two layers (0–10 cm and 10–20 cm). For all the calculations, statistical significance was set at $p \leq 0.05$.

3 Results and discussion

In general, soil aggregates differed visually depending on the sampling area (Figure 1). The shape and size of the soil aggregates from the top layer (0–10 cm) in both cases (compacted and uncompacted soil) were not very different. However, in the case of compacted soil, it was possible to observe their sharper edges and less roundness compared to uncompacted soil. In the 0–10 cm layer in compacted and uncompacted soil, the soil aggregates had a lumpy, cloddy shape, which means they were formed as a result of artificial disturbance – soil tillage. On the other hand, in the case of uncompacted soil, granular and worm-casts patterns (formed by the biotic activity of soil fauna) were observed on the surfaces of lumpy or cloddy aggregates. In the case of compacted soil in the 0–10 cm layer, the shapes of blocky, angular, and subangular soil aggregates were observed, with the rare occurrence of worm-casts.

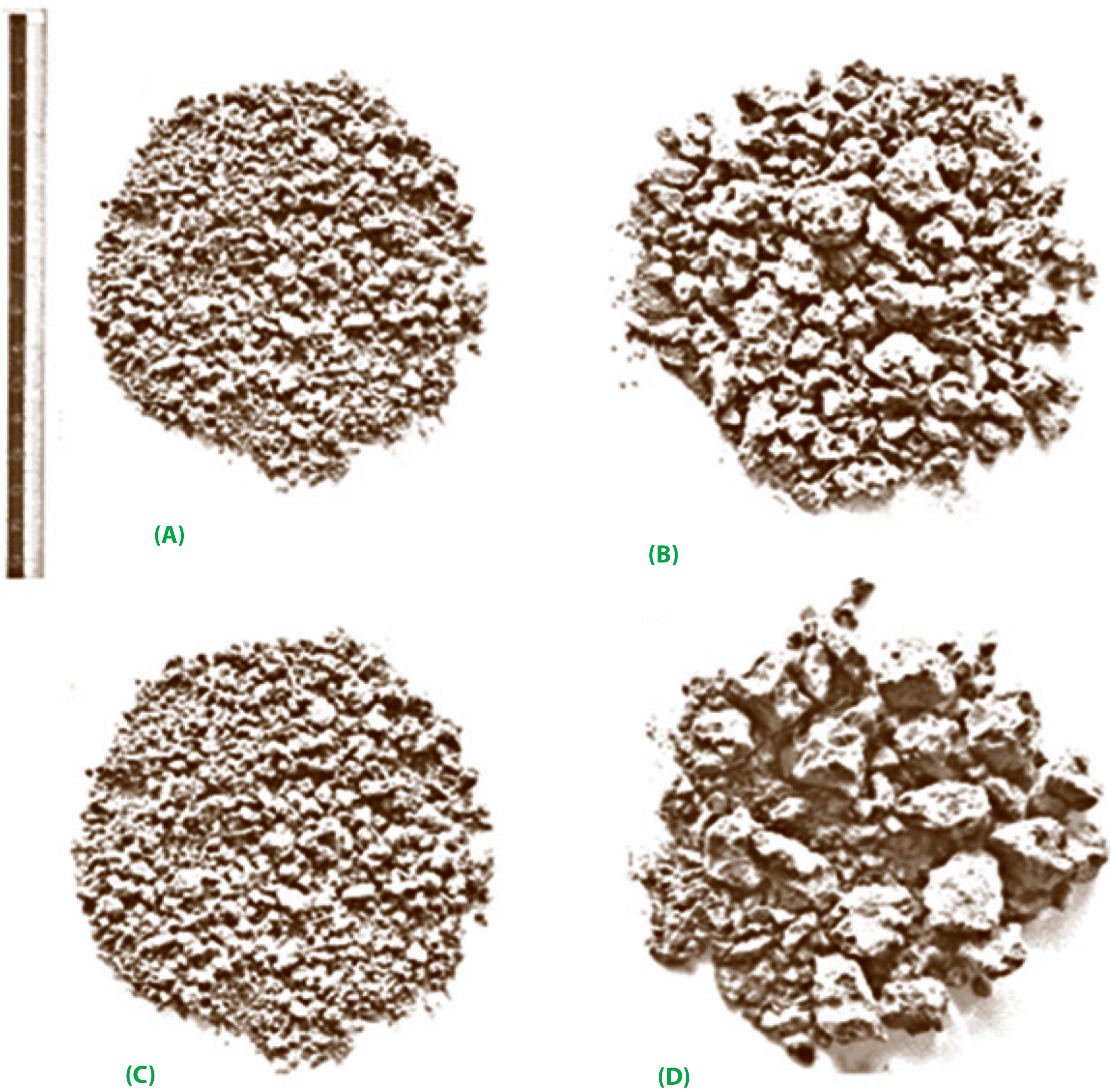

Figure 1 Shape of the soil aggregates in A, C) 0–10 cm layer, in B, D) 10–20 cm layer, in A, B) uncompacted soil, and in C, D) compacted soil

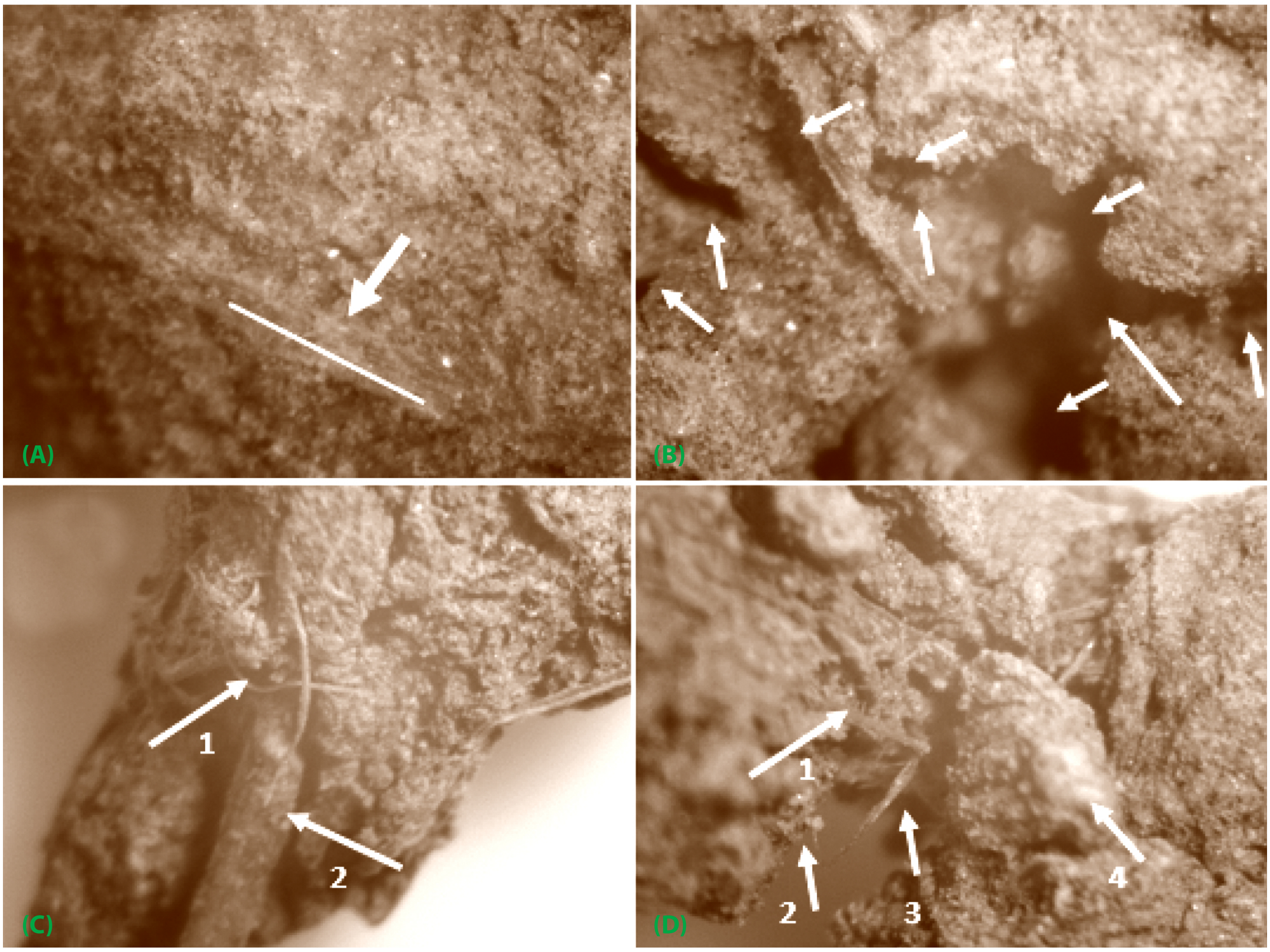

Figure 2 Details A) soil aggregate in compacted soil (arrow shows: pressed organic matter into aggregate without pores), B) soil aggregate in uncompacted soil (arrows show: voids and pores), C) soil aggregate in uncompacted soil (arrows show organic matter – comes from plant residues and roots. Arrow 1: small mineral particles oriented on the roots´ surface. Arrow 2: coarse particle of incorporated plant residue into soil aggregate), and D) soil aggregate in uncompacted soil (arrows 1–3: plant and root residues, arrow 4: worm-cast on the surface of micro-aggregate)

Thus, in this case, the formation of soil aggregates was ensured mainly abiotically – by separation. The effect of biotic mechanisms on the formation of soil aggregates was limited as a result of unfavorable conditions (compaction, lower porosity) for the development of soil fauna and microbial activity (Figure 2). A fundamental difference between compacted and uncompacted soil, especially in the shape of soil aggregates, was observed in the 10–20 cm layer. In the uncompacted soil shape of the soil aggregates indicated that their formation was mainly due to the biological activity. The shapes of soil aggregates were identified: granular, blocky subangular, but also worm-cast on the surface of crumbly and lumpy aggregates. To a lesser extent, soil aggregates formed by abiotic separation were also identified – their shape was angular. In the case of compacted soil, soil aggregates were formed mainly as a result of compaction and, to a lesser extent, fragmentation, but also abiotic separation. Their shape was blocky angular, blocky subangular, and platy. Platy soil aggregates were flat, with limited vertical dimension, generally oriented horizontally and usually overlapping. No worm-casts were observed on their surfaces. For this reason, we accept the hypothesis H1, because features of fragmentation and compaction were significant as a result of the soil tillage system at both depths on compacted and uncompacted soil.

Soil compaction strongly affects soil properties. Soil particles are pushed together at the expense of pores. Thus, compaction decreases total porosity, macroporosity, and connectivity between pores. As a result changes in the soil structure occur which affects limited growth of plant roots, and low soil microbial activity (Frey et al., 2009; Riggert et al., 2016). On the base of PCA analysis (Figure 3) it can be concluded that for most of the analyzed variables there is a greater variation between the depths than the degree of soil compaction.

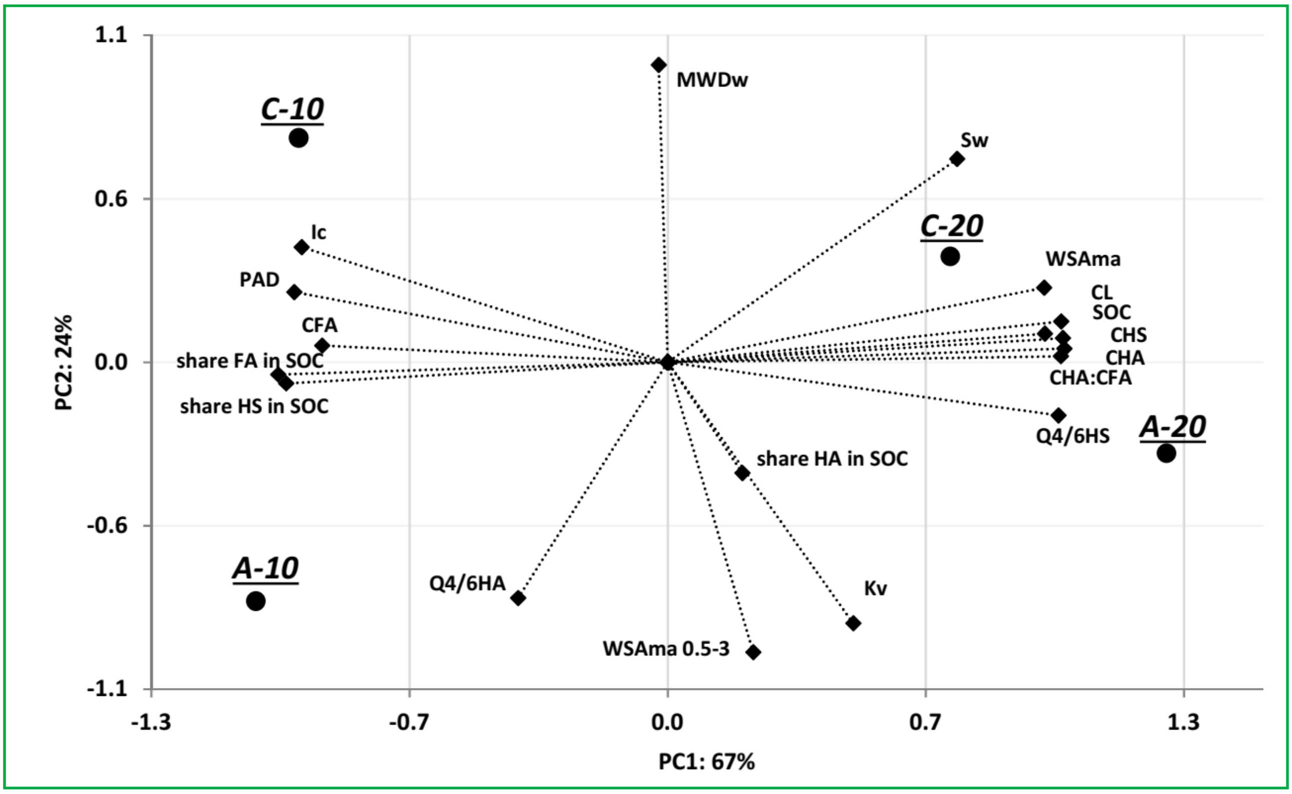

Figure 3 PCA results showing the relationship between SOM content, humic substances and soil structure and multivariate differences between objects i.e. combination of the layer and degree of soil compaction, A–10, A–20 uncompacted soil at 0–10 and 10–20, respectively, C–10, C–20 compacted soil at 0–10 and 10–20, respectively
WSAma – content of water-stable macro-aggregates, WSAma 0.5–3 – content of water-stable macro-aggregates in size fractions 0.5–3 mm, PAD – percentage of aggregate destruction, Sw – index of aggregate stability, MWDw – mean weight diameter of water-stable aggregates, Kv – vulnerability coefficient, Ic – crust index, C_{HS} – carbon of humic substances, C_{HA} – carbon of humic acids, C_{FA} – carbon of fulvic acids, SOC – soil organic carbon, $C_{HA} : C_{FA}$ – carbon of humic acids to carbon of fulvic acids ratio, $Q^{4/6}_{HS}$ – color quotient of humic substances, $Q^{4/6}_{HA}$ – color quotient of humic acids, C_L – labile carbon

Overall, only for MWDw, WSAma 0.5–3 mm, Kv, $Q^{4/6}_{HA}$, and % shape of HA in SOC the variation between compacted and uncompacted soil was greater. The content of SOM and HS was greater at the layer of 0–10 cm compared to 10–20 cm. However, the quality (higher $C_{HA} : C_{FA}$ ratio) and condensation of HS (lower color quotients $Q^{4/6}_{HS}$ and $Q^{4/6}_{HA}$) were greater at a depth of 10–20 cm. A higher $C_{HA} : C_{FA}$ ratio than 1 at the same time lower $Q_{4/6}$ ratio may be an indicative of more humified and highly condensed (aromatic) substances and more ancient origin. It means that humic substances have higher quality. Only in soil layer 0–10 cm was observed a statistically significant difference in C_{HA} and SOC content between compacted and uncompacted soil. Overall, however, no statistically significant differences in SOM content and HS between compacted and uncompacted soil were observed (Table 1).

As a result of soil compaction, slightly greater values of MWDw, Sw, WSAma, and WSAma of 0.5–3 mm were observed, which led to a decrease in aggregate destruction and a decrease in crust formation. However, no statistically significant differences were found for these variables in comparison with uncompacted soil. A statistically significant difference between compacted and uncompacted soil was observed in the case of DSA 1–3 mm ($P = 0.028$), DSA 3–5 mm ($P = 0.050$) for a depth of 0–10 cm, and WSAmi ($P = 0.007$) for a depth of 10–20 cm. In uncompacted soil, the content of DSA 1–3 and DSA 3–5 mm was respectively, 18 and 27% higher than in compacted soil. At the same time, in uncompacted soil, the content of WSAmi was higher by 221% compared to compacted soil at a depth of 10–20 cm (Figure 4). The obtained results partially confirm the hypothesis H2, since differences were not detected in all the evaluated parameters of the soil structure in the laboratory.

Correlation coefficients between SOM content, HS, and soil structure were determined both in uncompacted and compacted soils (Table 2). No statistically significant correlations were observed between SOC and soil structure, which may be explained by SOC concentration. In order to achieve good or very good water resistance and favor soil structure, the amount of carbon in the

Table 1 Results (means ±standard deviations) of group comparisons uncompacted (A) and compacted (C) soil for soil organic matter, humic substances parameters and two soil layers together with *p*-values based on *T*-test

Layer	Parameter	A	C	*P*-value
0-10 cm	C_{HS} (g/kg)	7.8 ±0.4	8.5 ±0.5	0.143
0-10 cm	C_{HA} (g/kg)	4.1 ±0.2	4.8 ±0.4	**0.045**
0-10 cm	C_{FA} (g/kg)	3.8 ±0.2	3.6 ±0.4	0.541
0-10 cm	SOC (%)	1.91 ±0.07	2.26 ±0.2	**0.049**
0-10 cm	% share HS in SOC	40.89 ±1.39	37.56 ±4	0.245
0-10 cm	% share HA in SOC	21.25 ±0.94	21.46 ±1.14	0.817
0-10 cm	% share FA in SOC	19.64 ±0.45	16.1 ±3.09	0.121
0-10 cm	$C_{HA} : C_{FA}$	1.08 ±0.02	1.36 ±0.2	0.078
0-10 cm	$Q^{4/6}_{HS}$	4.83 ±0.17	4.99 ±0.35	0.517
0-10 cm	$Q^{4/6}_{HA}$	4.28 ±0.23	4.26 ±0.12	0.880
0-10 cm	C_L (mg/kg)	2156 ±365	2816 ±302	0.074
10–20 cm	C_{HS} (g/kg)	6.6 ±1.1	6.4 ±0.4	0.804
10–20 cm	C_{HA} (g/kg)	3.4 ±0.3	3.5 ±0.7	0.972
10–20 cm	C_{FA} (g/kg)	3.1 ±1.4	2.9 ±0.3	0.883
10–20 cm	SOC (%)	1.69 ±0.35	1.78 ±0.45	0.794
10–20 cm	% share HS in SOC	39.08 ±2.57	36.96 ±6.51	0.628
10–20 cm	% share HA in SOC	21.52 ±5.94	19.53 ±1.78	0.609
10–20 cm	% share FA in SOC	17.56 ±5.03	17.43 ±5.48	0.977
10–20 cm	$C_{HA} : C_{FA}$	1.38 ±0.83	1.21 ±0.4	0.757
10–20 cm	$Q^{4/6}_{HS}$	4.73 ±0.16	4.86 ±0.22	0.433
10–20 cm	$Q^{4/6}_{HA}$	4.11 ±0.12	4.09 ±0.02	0.755
10–20 cm	C_L (mg/kg)	1778 ±340	1989 ±519	0.589

WSAma – content of water-stable macro-aggregates, WSAma 0.5–3 – content of water-stable macro-aggregates in size fractions 0.5–3 mm, PAD – percentage of aggregate destruction, Sw – index of aggregate stability, MWDw – mean weight diameter of water-stable aggregates, Kv – vulnerability coefficient, Ic – crust index, C_{HS} – carbon of humic substances, C_{HA} – carbon of humic acids, C_{FA} – carbon of fulvic acids, SOC – soil organic carbon, $C_{HA} : C_{FA}$ – carbon of humic acids to carbon of fulvic acids ratio, $Q^{4/6}_{HS}$ – color quotient of humic substances, $Q^{4/6}_{HA}$ – color quotient of humic acids, C_L – labile carbon
significant differences at $p \leq 0.05$ were marked in bold

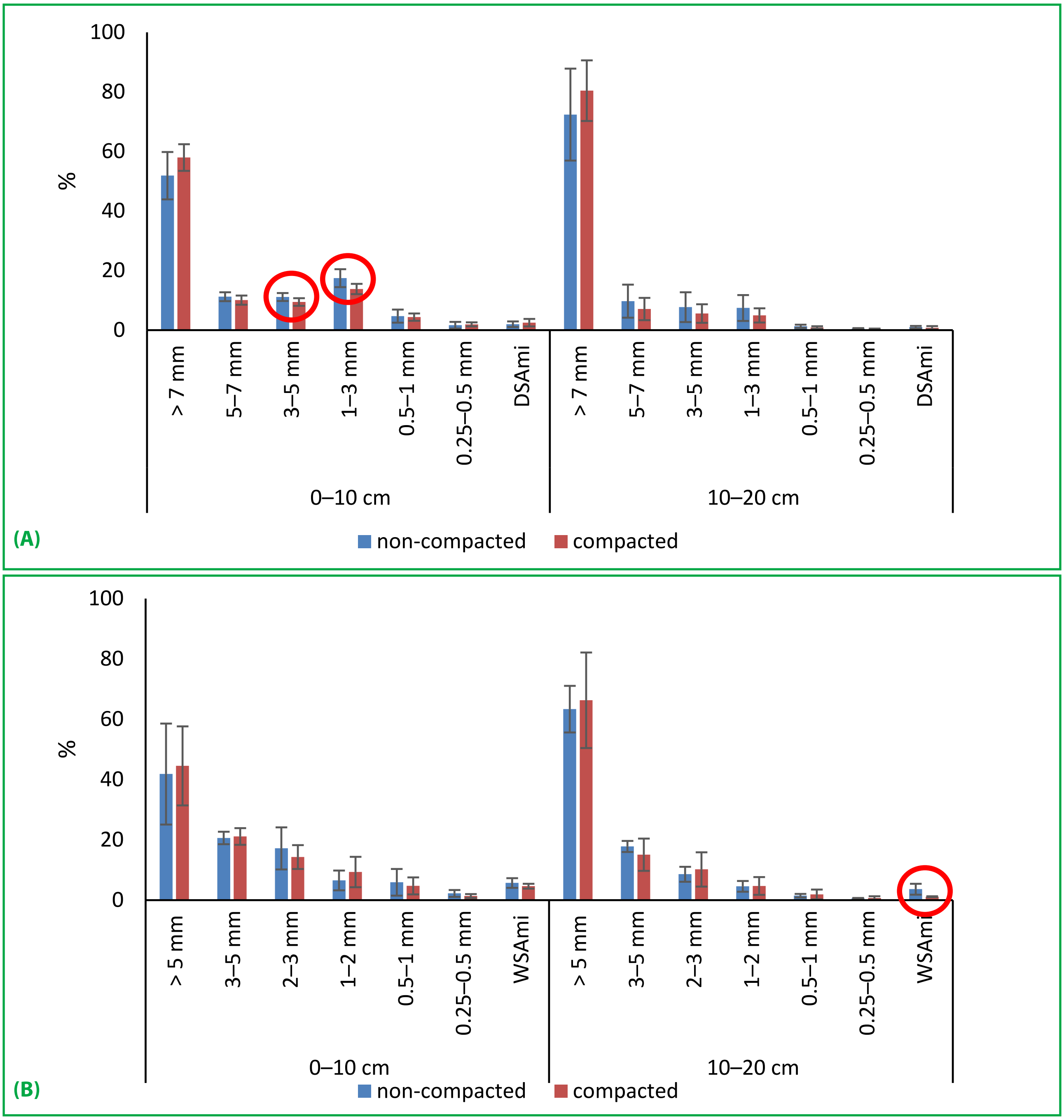

Figure 4 Contents of DSA (A) and WSA (B) in uncompacted and compacted soil
group comparison based on *T*-test; significant differences at $p \leq 0.05$ are marked in red circles

soil should be very high, for mineral soils more than 4%. There is a strong relationship between the water resistance of aggregates and the content of soil organic carbon (carbon fraction >3%). However, in soils with a low carbon content (<2%), these correlations are much weaker and do not allow an unambiguous assessment of the leading role of organic carbon in the formation of water–stable aggregates (Levy and Mamedov, 2002). In our case, the average SOC for compacted and uncompacted soils were 1.37–2.06% and 1.51–2.45%, respectively. On the other hand, for uncompacted soil, statistically significant correlations were observed between the share of HS in SOC and WSAma, share of HS in SOC and PAD, share of HS in SOC and Sw. For the compacted soil, statistically significant correlations were observed between C_{HS} and WSAma, C_{HS} and Ic, C_{FA} and Sw, C_{FA} and MWDw, the share of HS in SOC and Kv, share of HA in SOC and WSAma 0.5–3, share of HA in SOC and MWDw, $Q^{4/6}_{HA}$ and WSAma, $Q^{4/6}_{HA}$ and Sw. These correlations were negative in most cases. A higher number of statistically

Table 2 The correlation coefficients between SOM content, humic substances and soil structure for the uncompacted and compacted soil

	C_{HS}	C_{HA}	C_{FA}	SOC	Share of			$C_{HA} : C_{FA}$	$Q_{4/6}$		C_L
					HS	HA	FA				
					in SOC				HS	HA	
Uncompacted soil											
WSAma	-0.304	-0.658	-0.015	0.082	**-0.947**	-0.381	-0.157	0.023	-0.237	0.121	-0.262
WSAma 0.5-3	0.157	0.351	0.024	0.013	0.345	0.116	0.084	-0.069	0.684	0.581	-0.168
PAD	0.287	0.615	0.007	-0.094	**0.939**	0.391	0.141	0.006	-0.021	-0.390	0.388
Sw	-0.104	-0.509	0.146	0.260	**-0.898**	-0.454	-0.045	-0.064	-0.603	-0.135	0.094
MWDw	-0.214	-0.439	-0.042	-0.021	-0.466	-0.154	-0.115	0.081	-0.665	-0.528	0.092
Kv	0.147	-0.379	0.288	0.144	0.050	-0.370	0.447	-0.466	0.425	0.700	-0.295
Ic	-0.516	0.152	-0.582	-0.421	-0.280	0.502	-0.738	0.717	-0.223	-0.652	-0.118
Compacted soil											
WSAma	**-0.867**	-0.732	-0.729	-0.577	-0.071	-0.544	0.143	-0.210	-0.444	**-0.904**	-0.714
WSAma 0.5–3	0.444	0.158	0.790	-0.155	0.730	**0.830**	0.526	-0.394	0.390	0.535	-0.048
PAD	0.580	0.579	0.316	0.591	-0.276	0.056	-0.354	0.310	0.495	0.745	0.741
Sw	-0.624	-0.352	**-0.860**	-0.099	-0.528	-0.695	-0.340	0.257	-0.603	**-0.812**	-0.256
MWDw	-0.577	-0.306	**-0.833**	0.006	-0.650	**-0.859**	-0.417	0.279	-0.375	-0.616	-0.108
Kv	-0.050	-0.350	0.549	-0.592	**0.841**	0.528	0.786	-0.701	0.297	0.119	-0.549
Ic	**-0.826**	-0.790	-0.517	-0.606	-0.015	-0.730	0.289	-0.450	0.106	-0.570	-0.610

WSAma – content of water-stable macro-aggregates, WSAma 0.5–3 – content of water-stable macro-aggregates in size fractions 0.5–3 mm, PAD – percentage of aggregate destruction, Sw – index of aggregate stability, MWDw – mean weight diameter of water-stable aggregates, Kv – vulnerability coefficient, Ic – crust index, C_{HS} – carbon of humic substances, C_{HA} – carbon of humic acids, C_{FA} – carbon of fulvic acids, SOC – soil organic carbon, $C_{HA} : C_{FA}$ – carbon of humic acids to carbon of fulvic acids ratio, $Q^{4/6}_{HS}$ – color quotient of humic substances, $Q^{4/6}_{HA}$ – color quotient of humic acids, C_L – labile carbon
statistically significant correlations are marked in bold

significant correlations were observed in compacted than uncompacted soil and overall, hypothesis H3 was rejected. Humic substances quality determined based on the $C_{HA} : C_{FA}$ ratio had no effect on soil structure in either compacted or uncompacted soil, but in the case of compacted soil, higher condensation of HA (aromaticity) increased WSAma and Sw. The prerequisite for the proper functioning of processes in the soil, and the subsequent formation of a favorable soil structure, is the provision of optimal conditions for humification of organic matter flowing into the soil. The obtained results show that such a condition of the soil was not achieved. As reported Itami and Kyuma (1995), during the decomposition of SOM, citrates, fulvates, oxalates, or acetates are formed in the soil suspension, which increases the dispersion of clay, and this overall has a negative effect on the soil structure.

4 Conclusions

All in all, we conclude that 12 years of no machinery passing through the field improves the soil structure, but does not significantly affect all soil organic matter and humic substances parameters. Machinery crossings through the field affects the shape of soil aggregates and the mechanisms of their formation. The biological formation of soil aggregates was completely absent in compacted soil. In uncompacted soil, their formation mechanism was more diverse. A significantly greater mean weight diameter of water-stable aggregates was found, but significantly lower content of water-stable macroaggregates in the size fraction of 0.5–3 mm and higher vulnerability of the soil structure in compacted than uncompacted soil. The relationships between soil organic matter content, humic substances, and soil structure were mostly negative and statistically more significant in compacted than uncompacted soil. Since no sufficiently convincing evidence was obtained about the positive influence of soil organic matter content and humic substances on soil structure, further study is necessary. Attention should be paid to a more detailed characterization of humic substances´ properties (the amount and type of organic matter flowing into the soil can also be great importance in this context) and other soil characteristics (soil pH, cations, cation exchange capacity, nutrient availability, and etc.) in compacted and uncompacted soil.

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