Effect of Different Tillage Systems on Soil Organic Carbon and Enzymatic Activity

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Abstract: The aim of the study was to compare the effect of conventional, simplified, and organic farming systems on changes in the content of soil organic carbon, organic matter fractions, total nitrogen, and the enzymatic activity. The research was conducted from 2016–2018 on arable land in the south-eastern part of Poland. The selected soils were cultivated in conventional tillage (C_Ts), simplified tillage (S_Ts), and organic farming (O_Fs) systems. The analyses were performed in soil from the soil surface layers (up to 25 cm depth) of the experimental plots. The highest mean contents of soil organic carbon, total nitrogen, and organic matter fractions were determined in soils subjected to the simplified tillage system throughout the experimental period. During the study period, organic carbon concentration on surface soil layers under simplified tillage systems was 31 and 127% higher than the soil under conventional tillage systems and organic farming systems, respectively. Also, the total nitrogen concentration in those soils was more than 40% and 120% higher than conventional tillage systems and organic farming systems, respectively. Moreover, these soils were characterised by a progressive decline in SOC and Nt resources over the study years. There was no significant effect of the analysed tillage systems on the C:N ratio. The tillage systems induced significant differences in the activity of the analysed soil enzymes, i.e., dehydrogenase (DH) and catalase (CAT). The highest DH activity throughout the experiment was recorded in the O_Fs soils, and the mean value of this parameter was in the range of 6.01–6.11 μmol TPF·kg^{-1}·h^{-1}. There were no significant differences in the CAT values between the variants of the experiment. The results confirm that, regardless of other treatments, such as the use of organic fertilisers, tillage has a negative impact on the content of SOC and organic matter fractions in the O_Fs system. All simplifications in tillage reducing the interference with the soil surface layer and the use of organic fertilisers contribute to improvement of soil properties and enhancement of biological activity, which helps to maintain its productivity and fertility.

Keywords: tillage systems; organic farming; dehydrogenase activity; catalase activity; fractions of soil organic matter

1. Introduction

The tillage system consists of processes modifying the physical, chemical, and biological properties of soils. Soil cultivation is aimed at creation of appropriate conditions for the growth and development of crops, which are directly reflected in their yields. Cultivation practices have an effect on soil water retention capacity, temperature, aeration, and the rate of decomposition of crop residues [1,2]. The choice of an appropriate tillage system is mainly dependent on the local soil conditions, climate, and type of crops [3]. The

application of suitable agricultural technological practices in arable land has an impact on soil productivity and fertility [4]. The progressive degradation of the soil environment caused by the use of heavy machinery and agricultural tools together with the intensified chemisation of agriculture necessitate the search for soil cultivation methods ensuring soil protection and restoration of natural biocoenoses, especially in areas with intensive agricultural production [5–7].

The oldest and most widespread tillage method (also in Poland) is the plough tillage system, also known as traditional or conventional ploughing. This system is based mainly on the application of the plough, which results in cutting and turning the top layer of soil [7,8]. This tillage system is labour-intensive and energy-consuming, as it also requires additional operations, e.g., harrowing or rolling. An undoubted advantage of the conventional tillage system is the adequate soil loosening and aeration, which creates more favourable conditions for the growth and development of crops. Nevertheless, conventional tillage exerts many adverse effects, as it contributes to excessive compaction of soils, higher susceptibility of soils to erosion, and accelerated organic matter mineralisation [2,5,9,10]. Consequently, long-term conventional tillage may cause loss of soil productivity and fertility [11]. An alternative tillage method is the simplified (no-till) tillage. Through minimisation or exclusion of certain agrotechnical treatments, this system helps to reduce the negative impact of agricultural activity on the soil environment. In the simplified tillage system, plant residues left in the field protect the soil and reduce erosive processes substantially. The use of plant residues in combination with minimal soil interference creates favourable conditions for the development of soil organisms and protects organic matter against accelerated mineralisation [1,2,5,12–14]. Measures for the maintenance and protection of soil fertility are also undertaken in the so-called organic farming system, which is a counteraction to the intensification of agriculture, especially to the excessive use of fertilisers and plant protection products [10,15–17]. The organic agriculture practices contribute to enhancement of the biological activity of soils, which is mainly achieved through an increase in the organic matter content. The increased organic matter content in soils from the organic system is the result of the use of catch crops, recycling of crop residues, application of natural fertilisers (including manure), and simplification of such agrotechnical procedures as ploughing [15,18,19]. The impact of various tillage systems on the physical, chemical, and biological properties of soil has been extensively investigated and documented in the literature. The available data show that the abundance of organic matter in the top layer of arable soils is substantially higher in the organic farming system than in the conventional system. Greater organic matter abundance in soils enhances the biological and biochemical activity of soils, increases biodiversity, provides suitable conditions for the growth and development of crops, and protects soils against erosion [10,11,14,16,19–25]. The management of the agricultural production space often increasingly requires measures for protection of soil organic matter, which is also one of the key objectives of EU policy [26]. The common agrotechnical treatments, especially monoculture or improper fertilisation used in intensive agriculture, intensify the mineralisation processes and the loss of humus accumulated in the soil. In addition to productivity loss, this increases the release of CO_2 into the atmosphere, thus contributing to climate change [27–29]. To estimate the impact of agricultural activity on the quantity and quality of soil organic matter, the total organic carbon content and the levels of soil organic matter fractions are determined. Humified organic matter, which is conventionally divided into humic acids (C_{HAs}), fulvic acids (C_{FAs}), and humins (C_H), is the microbiologically most stable reservoir of organic matter [13,30].

Enzymatic activity, i.e., a sensitive indicator of changes caused by various factors, is one of the elements in the assessment of soil environment fertility. Soil enzymes are the basic determinants of processes taking place in soil. They are natural mediators and catalysts in many important processes, e.g., the decomposition of organic matter or the flow of carbon, nitrogen, and other elements necessary for the proper growth and development of plants. Knowledge of the enzymatic activity and other soil properties can help to precisely estimate the impact of applied farming treatments on soil fertility and productivity. Given their role

in the environment, oxidoreductases (including dehydrogenases and catalases) are regarded as the most important enzymes, as they are directly involved in the biogeochemical carbon, nitrogen, phosphorus, and sulphur cycle in soils [4,31,32].

The aim of the research was to assess the variability of selected soil parameters (soil organic carbon, total nitrogen, fractions of soil organic matter, and enzyme activity) in private farms. These soils were used in a manner not imposed by the authors, and kept the burrows as defined by the farmers—conventional tillage systems, simplified tillage systems, and the organic farming system. Most research on the influence of different tillage systems on soil properties is based on strict field experiments with a known system of experimental factors [6,9,15]. In our research, we worked closely with farmers, and the obtained results allowed us to estimate the changes in selected soil properties under specific farming conditions.

2. Materials and Methods

2.1. Study Area and Sampling

The study was carried out on selected plots of arable land in the south-eastern part of Poland (Podkarpackie Province) from 2016–2018. The location of the study area is shown in Figure 1.

Figure 1. Location of the study area.

The arable land plots selected for the analyses were located in areas with similar physiographic, hydrological, and climatic conditions. The soil in the plots had a similar granulometric composition. Three groups of arable land (each with 6 plots) were selected for the study. They differed in the cultivation treatments, crop structure, and the type and doses of fertilisation with basic plant nutrients—NPK. The following experimental variants were established: C_Ts—soils subjected to the conventional (ploughing) system, S_Ts_-simplified system, and O_Fs—soils subjected to ploughing in the organic farming system. Detailed data on the agrotechnical treatments applied in each year of the experiment and on the doses of the basic plant nutrients (NPK) supplied with the fertilisation are summarised in Table 1. Figure 2 shows the structure of crops cultivated during the study in each research plot.

2.2. Determination of Soil Properties

Soil samples intended for the analysis of the soil properties were collected from the topsoil up to a depth of 25 cm. They were collected after plant harvesting in each study year. The particle size distribution in air-dry samples sieved through a 2-mm mesh sieve was determined with the laser diffraction method (Analysette 22, Fritsch, Idar-Oberstein, Germany). The pH value was determined in a 1:2.5 substrate-water suspension using a 4221 pH-meter (Hanna Instruments, Nusfalau, Romania). Electrical conductivity (EC) was analysed in a 1:5 substrate-water suspension with a HI 2316 EC-meter from Hanna

Instruments (Nusfalau, Romania). The total nitrogen content (Nt) was determined with the Kjeldahl method. Soil organic carbon (SOC) was determined using the Walkley–Black procedure [33]. The C:N ratio was calculated based on the SOC and Nt contents. The fractional composition of soil humus was determined in air-dry soil samples using the Kononowa–Bielczikowa method by extraction of fractions with a mixture of 1M NaOH and $Na_4P_5O_7$. The fractionation was performed to determine the following humified organic matter fractions: humic acids (C_{HAs}), fulvic acids (C_{FAs}), and humins (C_H). Based on content of the C_{HAs} and C_{FAs}, the C_{HAs}/C_{Fas} ratio was calculated [30,34].

Table 1. Crop rotation, fertilisation, and cultivation treatments used in the study.

Tillage System	Year	Cultivated Plants	Types of Fertilisers	Soil Fertilisation per Year (kg ha^{-1})			Cultivation Treatments and Tillage Depth (cm)
				N	P	K	
C_Ts	2016	winter wheat	inorganic	146–150	20–26	60–75	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
		winter rapeseed		150–190	26	80	
		soybean		15	22	63	
		winter barley		130	26	75	
	2017	maize	inorganic	165	30	150	Disc harrow (12–18 cm) Pre-winter ploughing (25 cm) Cultivating and sowing unit (10–15 cm)
		winter wheat		138–155	26	75	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
		winter rapeseed		160–220	31	87	
	2018	maize	inorganic	155	22	212	Disc harrow (12–18 cm) Pre-winter ploughing (25–30 cm) Cultivating and sowing unit (10–15 cm)
		winter wheat		115–190	22–31	63–87	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
S_Ts	2016	winter rapeseed	inorganic	155	31	58	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
		winter wheat		200	31	60	
		winter rapeseed		195	31	60	
	2017	sugar beets	inorganic	125–194	31	60	Disc harrow (12–18 cm) Cultivating and sowing unit (10–15 cm)
		maize		162	31	60	
		winter wheat		210	31	60	
		winter rapeseed		200	42	80	
	2018	winter wheat	inorganic	168–246	31	75	
		winter rapeseed		210	31	87	
O_Fs	2016	potatoes	organic	94	25	95	Pre-winter ploughing (25–30 cm) Cultivation unit (10–15 cm)
		winter wheat		94–118	24–31	108–135	
	2017	winter rapeseed	organic	160	44	166	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
		winter wheat		118	31	135	
		winter rapeseed		160	44	166	
	2018	potatoes	organic	71–118	18–31	81–135	Disc harrow (12–18 cm) Pre-winter ploughing (25–30 cm) Cultivation unit (10–15 cm)
		winter wheat		141	37	162	Pre-sow ploughing (18–22 cm) Cultivating and sowing unit (10–15 cm)
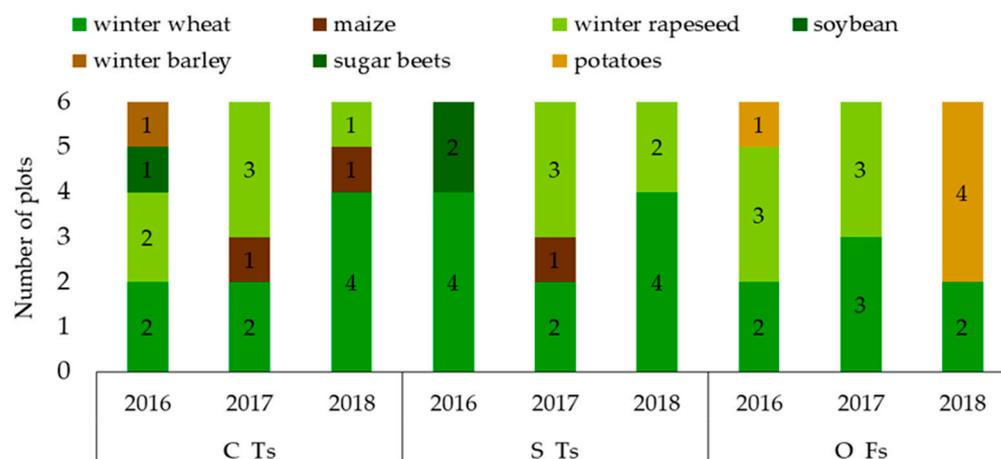
Figure 2. Plants cultivated on the experimental plots in the study years.

The activity of soil enzymes from the group of oxidoreductases, i.e., dehydrogenase (EC 1.1.1.1) and catalase, was determined in fresh soil samples with a natural moisture level. The dehydrogenase activity (DH) was determined with the use of the Lenhard method following the procedure proposed by Casida. It was determined by reduction of 2,3,5-tetrazolium chloride (TTC) to triphenyl formazan (TPF). To determine DH, an approx. 6-g aliquot of fresh soil was incubated with 1 mL of 3% TTC at 37 °C for 24 h. TPF was extracted using ethyl alcohol and analysed spectrophotometrically with a UV-Vis Schimadzu 2630 spectrophotometer. The activity of dehydrogenases (DH) was expressed in μmol of TPF kg^{-1} h^{-1} [35]. The catalase (CAT) activity was determined with the manganometric method according to the procedure proposed by Johnson and Temple [36]. Soil samples were incubated with the addition of hydrogen peroxide (a natural substrate of the enzyme). The H_2O_2 remaining in the soil and not decomposed by catalase was titrated with potassium permanganate in an acidic environment. The catalase activity was expressed in μmol H_2O_2 g^{-1} d.w. min^{-1}.

2.3. Statistical Analysis

All statistical analyses were performed using STATISTICA 13.3 software (StatSoft Inc., Tulsa, OK, USA). To show the existence of uniform groups of objects ($\alpha = 0.05$), the multiple comparison Tukey HSD test was performed following one-dimensional analysis of variance (ANOVA).

3. Results

3.1. Meteorological Conditions during the Study Years

The weather conditions in 2016–2018 varied (Figure 3). In all study years, the mean annual air temperature was higher than the average value in 1980–2015. During the experiment, 2018 was the coldest year (mean annual air temperature: 8.0 °C; mean temperature in the March–October growing season: 12.3 °C). The highest air temperatures, both the annual mean and the mean for the growing season, were noted in 2016 (9.5 °C and 13.1 °C, respectively). The same year (2016) was characterised by the highest annual precipitation rates and the highest value of this parameter for the growing season (16.8% and 19.8% higher rates than the multiannual precipitation sums, respectively). In turn, precipitation deficits were recorded in 2017 (6.3% and 32.9% lower rates than the multiyear mean, respectively).
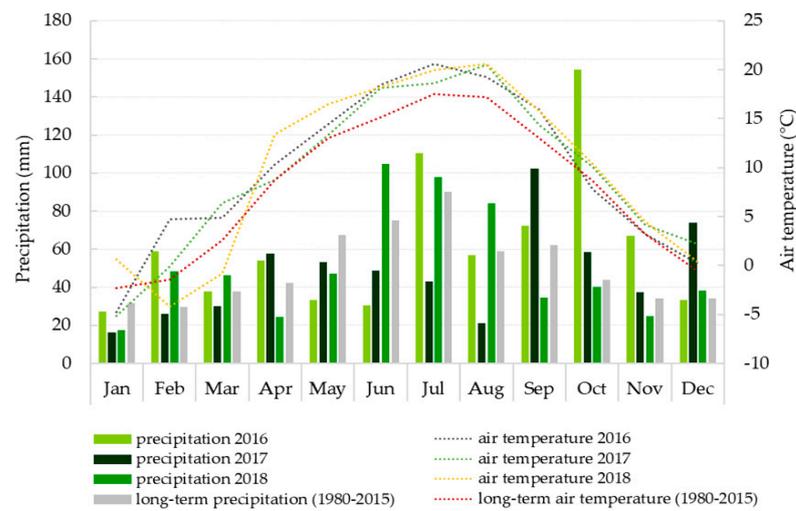
Figure 3. Meteorological conditions during the study period (2016–2018).

3.2. Selected Properties of the Investigated Soil in the Different Types of Tillage Systems

The soils collected from the selected plots subjected to the conventional tillage (C_Ts) contained on average 6.2% of sand, 83.5% of silt, and 10.3% of clay. In the C_TS variant, most soils had a granulometric composition corresponding to silt (Si), while one soil was identified as silty loam (SiL). The average content of sand, silt, and clay in the soils from the simplified tillage system (S_Ts) was 6.0, 79.2, and 14.8%, respectively. In terms of their granulometric composition, all soils in this group were classified as silty loam (SiL). In the O_Fs soils, the mean content of sand, silt, and clay was 1.5, 86.3, and 12.2%, respectively. All soils in this group were classified as silt (Si) (Table 2).

Table 2. Basic properties of arable soils in the different cultivation systems.

Object	Granulometric Composition of Soil (%)				pH_{H_2O}	EC (μS)
	Sand (2.0–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)	Granulometric Fraction (USDA)		
1 C_Ts	1	87	12	Si	7.58 [bc] ± 0.03	282 [b–d] ± 34
2 C_Ts	1	89	10	Si	7.20 [a–c] ± 0.56	174 [ab] ± 62
3 C_Ts	1	91	8	Si	7.58 [bc] ± 0.09	354 [d] ± 40
4 C_Ts	1	90	9	Si	7.7 [c] ± 0.08	248 [a–d] ± 37
5 C_Ts	31	63	6	SiL	7.02 [a–c] ± 0.74	256 [a–d] ± 67
6 C_Ts	2	81	17	Si	7.24 [a–c] ± 0.58	233 [a–d] ± 63
Mean ± SE C_Ts	6.2	83.5	10.3	-	7.39 [a] ± 0.11	257.8 [a] ± 16.8
1 S_Ts	2	81	17	SiL	6.79 [a–c] ± 0.45	210 [a–c] ± 33
2 S_Ts	1	83	16	SiL	6.89 [ab] ± 0.30	260 [ab] ± 46
3 S_Ts	1	82	17	SiL	6.71 [ab] ± 0.22	327 [ab] ± 59
4 S_Ts	1	80	19	SiL	6.53 [a] ± 0.09	169 [ab] ± 42
5 S_Ts	4	83	13	SiL	6.49 [a–c] ± 0.61	179 [a–d] ± 23
6 S_Ts	27	66	7	SiL	6.26 [ab] ± 0.35	167 [a] ± 29
Mean ± SE S_Ts	6.0	79.2	14.8	-	6.56 [c] ± 0.09	218.8 [ab] ± 16.2
1 O_Ts	1	89	10	Si	6.86 [a–c] ± 0.08	254 [d] ± 72
2 O_Ts	1	85	14	Si	6.58 [a–c] ± 0.27	143 [ab] ± 29
3 O_Ts	1	86	13	Si	7.31 [a–c] ± 0.13	365 [a] ± 44
4 O_Ts	1	89	10	Si	7.22 [a–c] ± 0.24	152 [a] ± 28
5 O_Ts	2	84	14	Si	6.92 [a–c] ± 0.35	133 ± 16
6 O_Ts	3	85	12	Si	7.00 [a–c] ± 0.09	126 ± 28
Mean ± SE O_Fs	1.5	86.3	12.2	-	6.98 [b] ± 0.07	195.5 [c] ± 22.6

Explanation: EC—electrical conductivity; Si—silt; SiL—silty loam. Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems (in the rows) according to the post-hoc Tukey HDS test.

In the groups of soils collected in the different tillage systems, the pH values determined in water were similar. The pH of the C_Ts soils ranged from 7.02 to 7.71 (mean 7.39) and did not differ significantly between the plots in this group. Moreover, the soils from the conventional tillage system were characterised by significantly higher pH values than the soils from the other objects. The pH value indicated the reaction of the soils. All the C_Ts and O_Fs soils were neutral, whereas the S_Ts soils were slightly acidic to neutral (Table 2).

The mean electrolytic conductivity (EC) values were in the range of 195.5–257.8 µS, with the highest values in the C_Ts group of soils and the lowest values in the O_Fs soils (Table 2).

3.3. Soil Organic Carbon (SOC), Total Nitrogen (Nt), and C:N Ratio in Soils from the Different Tillage Systems

The tillage system had a significant effect on the mean content of soil organic carbon (SOC) (Figure 3). In all study years, the highest mean SOC content was determined in the S_Ts soils, and the lowest level was exhibited by the O_Fs group. The mean SOC content in the S_Ts soils was in the range of 25.1–27.9 g kg^{-1}, with the highest level in the 1st year of the study. The SOC values determined for each plot in the S_Ts group were similar in the 1st and 2nd years of the experiment. In turn, they were characterised by high variability in the 3rd year, as evidenced by the large differences between the minimum and maximum value (Figure 4). The lowest mean SOC content was recorded in the O_Fs soils, compared to the other variants. The values determined for these soils showed low variability between the compared plots. Moreover, a clear trend towards a decline in the SOC content was observed in these soils during the consecutive years in comparison with the 1st year of the study. The initial SOC content in these soils was 13.3 g kg^{-1} in 2016 and 10.1 g kg^{-1} in 2018.
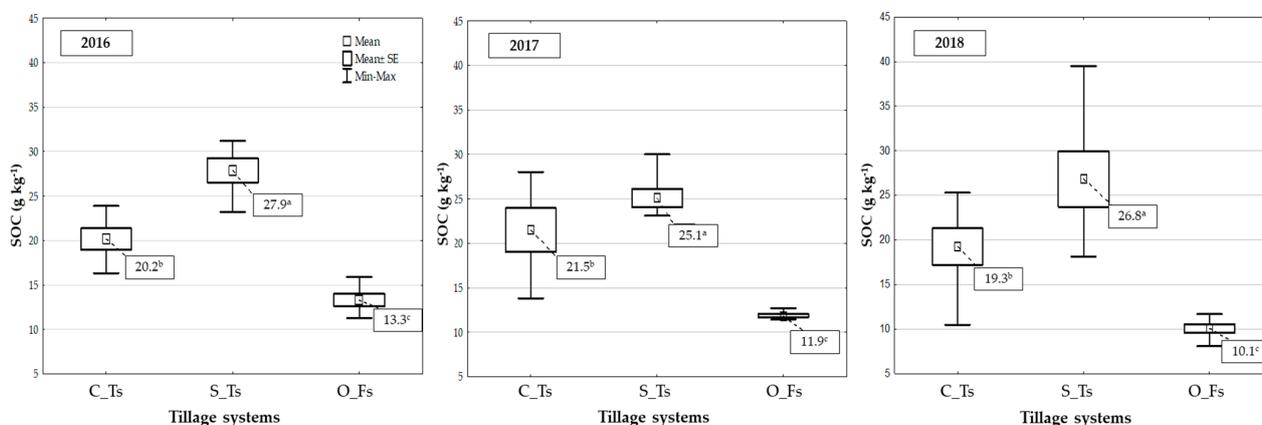
Figure 4. Content of SOC in soils from the different tillage systems during the study years (2016–2018). Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems according to the post-hoc Tukey HDS test.

Similar relationships were also observed for the content of Nt. As in the case of SOC, the highest mean Nt content was recorded in the S_Ts soils, and this value was significantly higher than in the other soil groups. The mean content of Nt in the soils of this group in the 1st and 2nd years of the study was the same, and the results obtained for the analysed plots exhibited low variability (Figure 5). As in the case of SOC, high variability of the results obtained for each plot was observed in the last year of the study, which is evidenced by the large differences between the minimum and maximum value of Nt (Figure 5). Relatively stable mean Nt content throughout the study was also determined in the C_Ts soils. As in the case of SOC, the lowest mean Nt content was determined in the O_Fs soils. It ranged from 1.25 g kg^{-1} to 0.97 g kg^{-1}, showing a clear downward trend with time compared to the 1st study year (Figure 5).
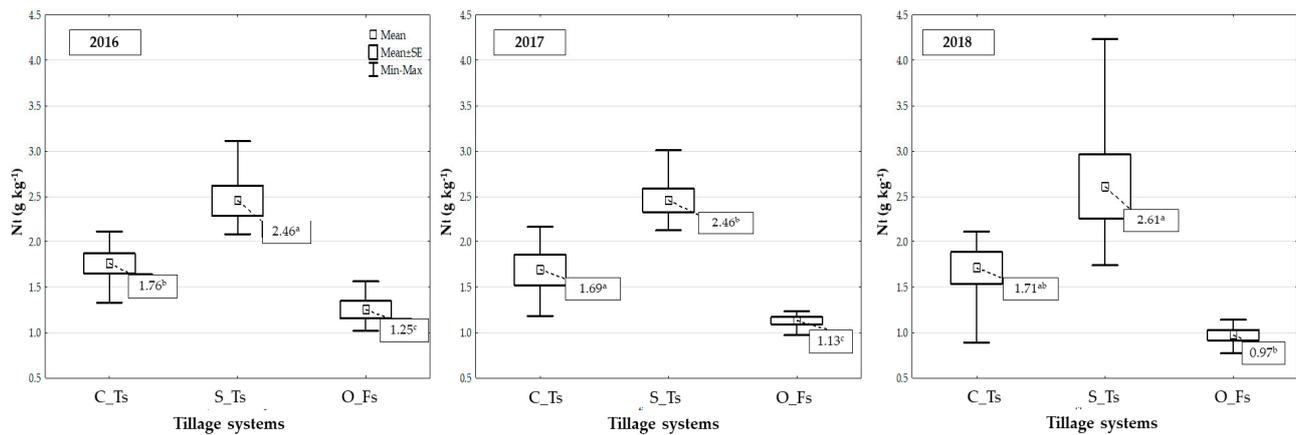
Figure 5. Content of total nitrogen (Nt) in soils from the different tillage systems during the study years (2016–2018). Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems according to the post-hoc Tukey HDS test.

The C:N ratio is directly associated with the SOC and Nt contents. Relatively low C:N ratios were noted in the analysed soils. These relationships were observed throughout the study. There was no significant effect of the cultivation systems on the mean value of the C:N ratio. In turn, considerable fluctuations of this parameter were observed in the soils from the individual plots, especially in the C_Ts soils (Figure 6).
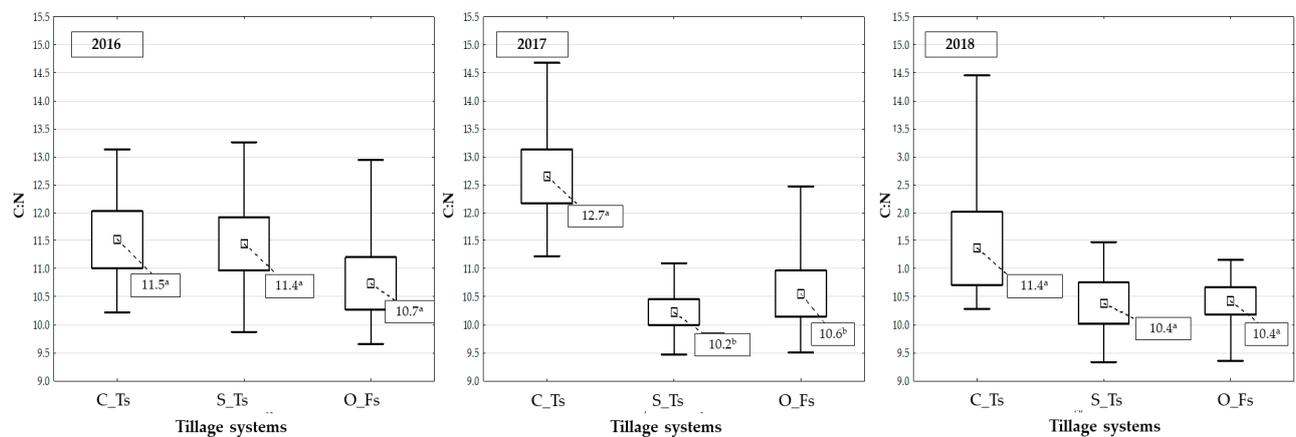
Figure 6. C:N ratio in soils from the different tillage systems during the study years (2016–2018). Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems according to the post-hoc Tukey HDS test.

3.4. Fractional Composition of Organic Matter

The process of organic matter fractionation consisted of the determination and calculation of the following values: carbon content after extraction in the mixture of 1M NaOH and $Na_4P_5O_7$ (C_{ext}), humic acid carbon (C_{HAs}), fulvic acid carbon (C_{FAs}), and humin carbon (C_H).

The mean C_{ext} values ranged from 5.82 to 16.49 g kg^{-1} (Table 3). The parameter depended on the tillage system: it had the highest values in the S_Ts soils and the lowest value in the O_Fs system. Moreover, the determined C_{ext} values exhibited large variation between the individual experimental plots, as evidenced by the large differences between the minimum and maximum values. Similar relationships were also found in the case of the other organic matter fractions (Table 3). The C_{HAs}/C_{FAs} ratio is directly related to the content of humic and fulvic acids. The values of the calculated C_{HAs}/C_{Fas} ratio ranged from 0.91 to 1.21 and did not differ significantly between the different experimental

variants (Table 3). In addition to the C_{HAs}/C_{FAs} parameter, the quality of soil humus is determined based on the percentage share of its individual fractions in the SOC pool (Figure 7). Regardless of the cultivation systems and the study year, the humin (C_H) fraction represented the highest proportion in the SOC pool. In the individual years of the study, C_H accounted for 44.5–55.0%, 41.4–56.6%, and 45.9–55.3% of the SOC pool in the C_Ts, S_Ts, and O_Fs soils, respectively (Figure 7). The highest share of C_H in the SOC pool in all the experimental variants was recorded in the 2nd year of the study. In the last year, there was a clear decrease in the proportion of the C_H fraction accompanied by an increase in the proportion of the C_{FAs} fraction in the SOC pool in all the experimental variants (Figure 7).

Table 3. Soil organic matter fractions in soils from the different tillage systems (mean for the study years 2016–2018).

Tillage System	Parameters	Soil Organic Matter Fraction (g kg^{-1})				
		C_{ext}	C_{HAs}	C_{FAs}	C_{HAs}/C_{FAs}	C_H
C_Ts	Mean	8.89 [b]	4.16 [ab]	4.88 [b]	0.91 [a]	11.04 [b]
	Min	5.30	1.44	3.03	0.37	5.20
	Max	14.13	8.66	9.71	2.08	19.00
	SE	0.59	0.39	0.37	0.11	0.92
S_Ts	Mean	16.49 [a]	5.41 [a]	6.49 [a]	0.91 [a]	14.68 [a]
	Min	7.37	2.93	3.62	0.37	5.00
	Max	23.77	11.12	12.65	2.08	22.60
	SE	0.83	0.48	0.52	0.11	0.89
O_Fs	Mean	5.82 [c]	2.99 [c]	2.83 [c]	1.22 [a]	6.20 [c]
	Min	4.38	1.19	1.42	0.37	3.00
	Max	8.32	4.37	4.93	2.51	11.10
	SE	0.27	0.21	0.24	0.15	0.39

Explanation: C_{ext}—carbon extracted in 1M NaOH and $Na_4P_5O_7$ mixture; C_{Has}—humic acid carbon; C_{FAs}—fulvic acid carbon; C_H—humin carbon. Mean values ($n = 18$) ± standard error. Identical superscripts denote no significant ($p > 0.05$) differences between soils from the different tillage systems (in the rows) according to the post-hoc Tukey HDS test.
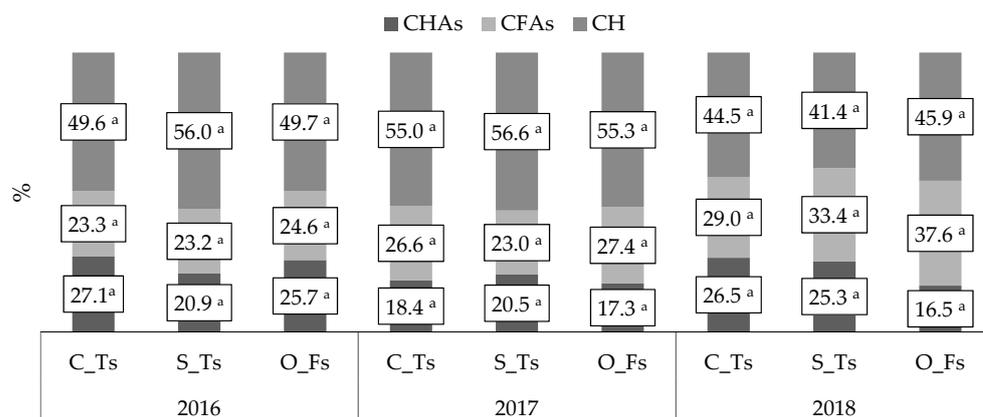
Figure 7. Share of soil organic matter fractions in the SOC pool in the different tillage systems. Mean values ($n = 6$). Identical superscripts denote no significant ($p > 0.05$) differences between soils from the different tillage systems in the particular year according to the post-hoc Tukey HDS test.

3.5. Soil Enzymatic Activity

In the present study, the dehydrogenase (DH) activity differed significantly depending on the cultivation systems and the year of the study (Figure 8). The highest DH activity was recorded in the O_Fs soils throughout the study. The mean DH value in this group of

soils was very stable and ranged from 6.01 to 6.11 μmol TPF·kg^{-1}·h^{-1}. Similarly, the mean DH activity in the S_Ts soils was high and ranged from 4.96 to 5.32 μmol TPF·kg^{-1}·h^{-1} throughout the study. In comparison with the O_Fs and S_Ts systems, the mean DH activity in the C_Ts soils was significantly lower and ranged from 3.59 to 4.85 μmol TPF·kg^{-1}·h^{-1} during the study years. The comparison of the S_Ts and O_Fs soils revealed no significant differences in the DH activity in the 1st and 3rd study years. In turn, the mean DH activity in the 2nd year of the experiment was significantly higher in the O_Fs soils (Figure 8).
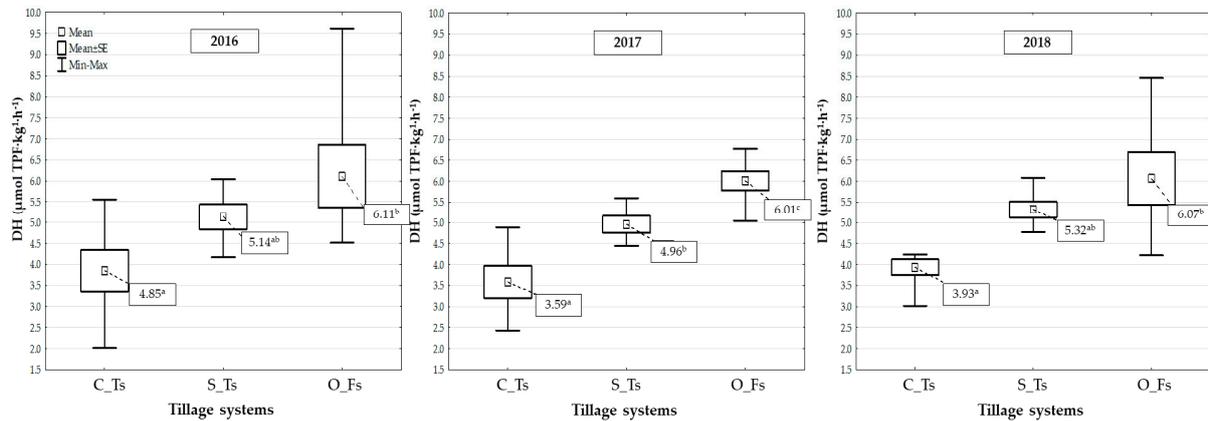
Figure 8. Dehydrogenase activity (DH) in soils from the different tillage systems during the study years (2016–2018). Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems according to the post-hoc Tukey HDS test.

The highest catalase (CAT) activity was determined in the O_Fs soils. In the study years, it ranged from 0.156 (2nd year) to 0.177 (1st year) mg H$_2$O$_2$·g^{-1} d.w·min^{-1}. Despite the higher values of the activity of this enzyme in the O_Ts soils, there were no significant differences in comparison with the other experimental —C_Ts and S_Ts (Figure 8). It was also observed that, mainly in the 1st and 3rd years of the experiment, the CAT activity in the O_Fs soils exhibited high variability, as evidenced by the large differences between the maximum and minimum values (Figure 9).
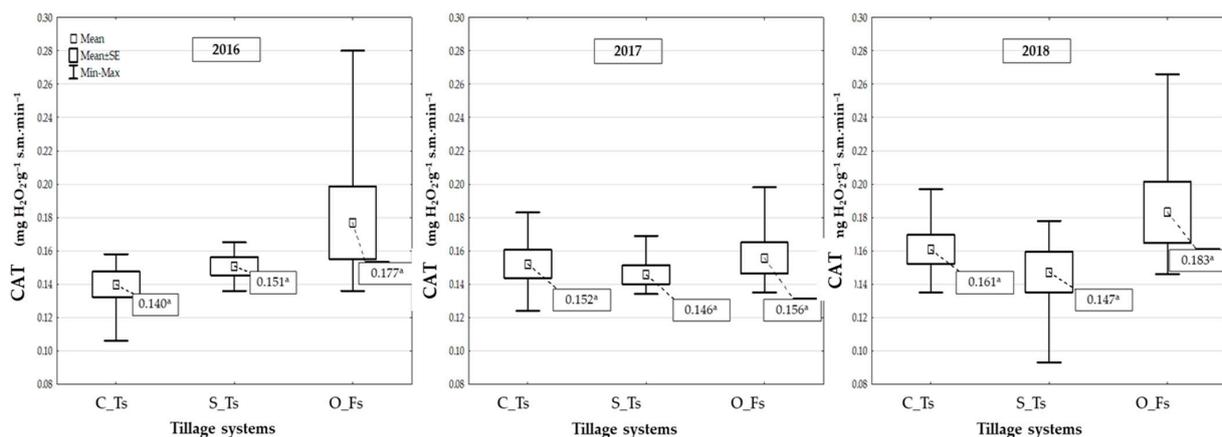
Figure 9. Catalase activity (CAT) in soils from the different tillage systems during the study years (2016–2018). Mean values (*n* = 18) ± standard error. Identical superscripts denote no significant (*p* > 0.05) differences between soils from the different tillage systems according to the post-hoc Tukey HDS test.

4. Discussion

The organic matter content in soils and especially its most important component, i.e., soil humus, undergoes continuous quantitative and qualitative changes; therefore, it is not

a constant value [37]. Agrotechnical treatments exert an impact on the accumulation of soil organic matter. They determine e.g., the rate of the decomposition of post-harvest residues or natural fertilisers delivered to the soil, which is reflected in the quality and chemical composition of soil humus [38]. The negative impact of conventional tillage on soil humus content, i.e., an increase in its mineralisation rate, is widely documented in the literature. Simplified tillage and organic farming systems contribute to an increase in the soil humus level [1,2,5,12,14]. The present study has confirmed the beneficial effect of S_Ts on the SOC content. Regardless of the applied fertilisation (mineral or organic) and the crops cultivated, the highest soil organic carbon and total nitrogen content were on soils under simplified tillage systems compare to soils under conventional tillage and organic farming. The mean concentration of organic carbon in soil surface layers under S_Ts was more than 30% higher than in soils under C_Ts and more than 120% higher than in soils under O_Fs (Figure 3). It indicates that any simplifications in the tillage systems and reduced interference with soil surface layers most exposed to the impact of agrotechnical treatments enhance organic matter accumulation.

In the simplified tillage system, plant residues are left on the soil every year, and their decomposition and transformation increase the amount of organic carbon in the topsoil [8]. Moreover, the reduced cultivation intensity slows down the rate of organic matter decomposition, which undoubtedly contributes to an increase in its content in the soil [7]. It is commonly believed that conventional (plough) tillage, in contrast to simplified tillage, has an especially negative effect on the content of organic matter through the strong and systematic interference with the soil system and may reduce the content of organic matter in the soil by up to 50% within 20 years [39,40]. As mentioned above, in soils under organic farming systems, the lowest organic carbon content was found. As in the conventional system, plowing was one of the cultivation treatments in these soils. Regardless of regular natural fertilisation applied on these soils, interference with the surface layers of these soils due to plowing caused a higher rate of transformation and mineralization, which was probably affected on organic carbon losses.

It is well known that the type of crop plants and crop rotation are the most important factors increasing the organic carbon content in soil [19,40]. This is associated with, for example, the amount of post-harvest residues and requirements for the preparation of the land for crop cultivation [23]. In general, the levels of organic carbon and total nitrogen are higher in soils where crop rotation is applied than in soils where plants are grown in monoculture [24,40]. Fabaceae plants and their mixtures with grasses as well as pulses have high organic matter reproduction potential. In turn, root crops and maize contribute to depletion of soil organic matter [40]. They produce small amounts of crop residues, and they are planted in wide rows. Additionally, the late achievement of plant cover density intensifies the processes of mineralisation of organic matter, which does not support its accumulation in soils. Cereals and oilseed plants exert a low negative or neutral impact. Winter wheat and oilseed rape with some amounts of maize and soybean were most often cultivated in the analysed conventional tillage soils (C_Ts) (Figure 2). Similarly, cereals, oilseed crops, and occasionally sugar beets and maize were most often grown in the S_Ts soils. The lowest levels of organic carbon in the organic farming (O_Fs) soils may have been caused by the farming treatments (ploughing) and the crop structure, as winter wheat, oilseed rape, and potatoes were most often grown in these soils. The amount of cereal residue is approximately 3-fold higher than that of root crop residues. Moreover, the yield of arable crops in soils in the organic farming system is approximately 19% lower than in the conventional tillage system. This in turn is associated with lower amounts of plant residues, which are a source of soil organic matter [17]. It should be emphasised, however, that in addition to their amount, the chemical composition of crop residues is important, as it determines their degradation and transformation in soils. Post-harvest residues of oilseed rape and wheat are characterised by high C:N and C:P ratios and high content of lignin, which is difficult to degrade in the soil [13]. Depending on the species or cultivar, crops can influence the biochemical and microbiological activity of the soil

in a variety of ways through the effect of their root exudates. Thus, they can exert an indirect effect on the processes of transformation and accumulation of organic matter in the soil [25]. In soils with high biological activity, post-harvest crop residues are decomposed rapidly. Depending on the cultivation system and soil biological activity, the quantitative and qualitative transformations may have two opposite directions, i.e., mineralisation or humification [24,37,41].

The properties of soil humus depend on many factors and, simultaneously, they are specific to the types of soil. Humic acids are the main components of soil humus determining its properties and role in the natural environment. It is widely known that the content of humic acids in arable soils is primarily determined by the fertilisation type [13,42].

The tillage system significantly differentiated the content of the organic carbon fractions. The highest mean content of C_{HAs}, C_{FAs}, and C_H was detected in the S_Ts soils, and the lowest value was reported for the O_Ts soils (Table 3). As shown in Figure 6, the tillage system did not exert a significant effect on the percentage of the organic carbon fractions. In all the experimental variants, the C_H fraction accounted for the highest percentage in the total organic carbon content (SOC) throughout the study years. The contribution of C_{HAs} and C_{Fas} to the SOC pool exhibited slight fluctuations depending on the cultivation systems and the study year (Table 3). Humins are the most resistant fraction to microbiological decomposition and leaching; hence, their higher levels in soils indicate relative persistence and stability of soil humus. It can be assumed that the C_H content determined in the analysed soil groups indicate relatively stable and unchangeable resources of this element. The C_{HAs}:C_{FAs} ratio is directly associated with the C_{HAs} and C_{FAs} contents. Higher values of this ratio are typical of more fertile soils with a high degree of organic matter humification. The values of the C_{HAs}/C_{Fas} ratio did not differ significantly between the experimental variants, which may indicate that none of the cultivation systems used disturbed the soil system equilibrium in the specific habitat conditions [13].

Nitrogen is a well-known essential element required for the proper development of crops. In soils, it usually occurs in insufficient amounts to meet the nutritional needs of plants; therefore, it is supplied with mineral or organic fertilisers, often in amounts substantially exceeding the recommended doses. The mean content of Nt in the analysed soil levels differed significantly between the experimental variants (Figure 5). As in the case of the SOC content, the lowest Nt content was determined in the O_Fs soils. The mean Nt content in these soils not only had the lowest value compared to the other experimental plots but also clearly declined over time. The differences in the Nt levels in the soils of the experimental variants resulted from several factors, e.g., the organic matter content, the crop type, or the applied mineral and organic fertilisation. In the analysed cultivation systems, the doses of N per pure component supplied to the arable crops varied largely irrespective of the type of fertilisation used (mineral or organic) (Table 1). The highest level of N fertilisation per pure component was applied to the most commonly cultivated plants (winter wheat and winter oilseed rape) in the S_Ts soils, compared to the other cultivation systems. The soils in the O_Fs group were fertilised only with organic fertilisers (manure). Fertilisation with manure enhances the accumulation of organic matter and plant nutrients and improves the soil retention capacity through improvement of the soil structure. On the other hand, inorganic fertilizers indirectly influence SOC concentration by increasing crop yields and thereby increasing the return of crop residues to the soil. As proven in the present study, fertilisation alone does not produce an increase in the organic matter and Nt contents in soils, but some simplification of the cultivation system is required. Ploughing was the main tillage treatment applied in the O_Fs soils. As frequently emphasised before, the ploughing tillage system increases soil oxygenation, thereby contributing to faster mineralisation of organic matter and leaching of simple inorganic compounds generated in this process into deeper layers of the soil profile and then into groundwater [27–29]. The O_Fs soils were also characterised by the highest biological activity, which may have accelerated the mineralisation of exogenous organic matter supplied with the fertilisers.

As shown by various investigations, the content of some organic matter fractions, such as humic acids, is closely related to the content of total nitrogen in the soil, as this element is one of the main components of these compounds [42,43]. This relationship was also confirmed in the present study, i.e., the highest mean C_{HAs} content was determined in the S_Ts soils, which exhibited the highest Nt level as well, compared to the other objects (Table 3). In turn, the lowest Nt and C_{Has} levels were recorded in the O_Fs soils, which may have been associated with the amount of nutrients supplied with the fertilisers. In the case of the O_Fs soils, the natural fertilisation (manure) provided the lowest amounts of pure N, in comparison with the other experimental objects, which was undoubtedly correlated with the content of this element in the soil.

The C:N ratio is directly associated with the soil SOC and Nt contents. It is a very important indicator determining the activity of soil microorganisms and thus influencing the C and N cycle and the decomposition of post-harvest crop residues [44]. Relatively lower values of the C:N ratio are crucial for the utilisation of C and N by soil microorganisms, which has an impact on the release of larger amounts of nutrients into the soil and thus on soil fertility. Therefore, the C:N ratio provides important information about the C and N cycle in soils [45]. In general, the impact of cultivation systems on the C:N ratio is poorly known [46]. The present study did not confirm unequivocally the effect of different tillage systems on the value of this parameter. The mean values of the C:N ratio in the analysed cultivation systems exhibited relatively small fluctuations in the study years (Figure 6). Noteworthy, the values of this parameter may also depend on meteorological conditions, i.e., the higher degree of nitrogen leaching from the soil induced by intense rainfall results in higher values of the C:N ratio. The air temperature has a significant impact on the value of this parameter as well. The higher the temperature, the lower the C: N ratio values.

Soil enzymatic activity, which varies depending on the farming systems and fertilisation, is a sensitive indicator of environmental changes [4,25,31,32,47,48]. In the group of soil enzymes, the activity of dehydrogenase is highly important, as this intracellular enzyme provides information about the biological activity of soil microflora [25]. The dehydrogenase activity depends on various factors in the soil, e.g., moisture, redox potential, and organic matter content [48].

In the present study, the highest values of the activity of enzymes from the oxidoreductase group were observed in the O_Fs soils, and this trend persisted throughout the study. This confirms the conclusions reported in the literature on the increased biochemical activity and biodiversity of soils in organic farming systems *versus* conventional tillage [16,21,32]. This is mainly related to the discontinuation of the application of large amounts of mineral fertilisers and chemical plant protection products, as is the case in intensive agriculture. Soil enzymatic activity depends on different factors associated with soil properties (e.g., pH, SOC, nutrient content, texture) and environmental factors (e.g., precipitation, temperature, sunshine). As reported by Acosta-Martínez and Waldrip (2014), enzyme activities are higher in clay and loamy soils than in sandy soils [49]. Additionally, enzyme activities have also been used as an early indicator of changes in soil quality because they are more sensitive to changes in land use or management practices than other soil properties [50]. It is well known that any simplifications of cultivation and reduction of interference with the soil surface layers increase the enzyme activity of soils [3]. These observations were also confirmed in the present analyses of the activity of the selected soil enzymes, as the highest enzyme activity was determined in the O_Fs soils and in the S_Ts soils. This also proves that the reduction of mineral fertilisation on the one hand and the lower interference with the topsoil on the other hand contribute to maintenance of soil fertility and ensure achievement of stable crops.

5. Conclusions

The research assessed the influence of different tillage systems (conventional, simplified, and organic farming) on selected soil properties (organic carbon content, total nitrogen content, organic matter fractional composition, and enzymatic activity). The effect of tillage

systems on selected soil properties was assessed on arable soils of private farms. The conclusions of the conducted research are as follows:

1. Regardless of the applied fertilisation (mineral or organic) and the crops cultivated, the highest soil organic carbon and total nitrogen content were on soils under simplified tillage systems. The mean concentration of organic carbon in soil surface layers under simplified tillage systems was more than 30% higher than in soils under conventional tillage systems and more than 120% higher than in soils under organic farming. It indicates that any simplifications in the tillage systems and reduced interference with soil surface layers most exposed to the impact of agrotechnical treatments enhance organic matter accumulation.

2. The lowest soil organic carbon and total nitrogen concentration were found in soils under organic farming. This indicates that not only organic fertilisation but also any simplification of tillage systems are important considerations to maintaining organic carbon resources.

3. Compared to other tillage systems, the soils of the organic farming system were characterised by the highest enzymatic activity. Limitation of the chemisation of agriculture through organic farming contributes to an increase in the biochemical activity of soils. Mean dehydrogenase activity on soil surface layers under organic farming systems during the study years was higher than simplified tillage systems and conventional tillage systems by 18 and 60%, respectively. In the long term, organic farming systems can help maintain natural fertility and productivity of soils, thus ensuring the stability of crops and food security for future generations.

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