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The Effects of Catch Crops and Tillage Systems on Selected Physical Properties and Enzymatic Activity of Loess Soil in a Spring Wheat Monoculture

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Abstract: This study was aimed at comparing physical soil quality parameters and soil enzymatic activity in a three-year spring wheat monoculture affected by the incorporation of biomass of selected catch crops into the soil using two systems of tillage (conventional plough tillage and conservation tillage). We tested the suitability of the following catch crop plants: white mustard, lacy phacelia, and mixed legumes (faba bean + spring vetch) and compared these to the control treatment. This research was carried out in the period 2014–2016 in Czesławice (central Lublin region, Poland). Catch crops promoted improved soil structure, soil particle-size distribution, soil bulk density, and soil moisture content. Tillage systems had a smaller impact on the soil physical parameters. Plough tillage contributed to improved soil moisture content in a deeper layer (15–20 cm). On the other hand, the above-mentioned tillage system influenced adversely soil compaction and bulk density. Catch crops caused an improvement in the soil particle size distribution, resulting in a higher percentage of the finer soil fractions. Moreover, the catch crops positively affected soil bulk density and soil compaction. The study has proven that enzymatic tests are good indicators to discriminate between soil sites under study in dependence on the catch crop and tillage system. Conservation tillage significantly stimulated the activities of the studied enzymes, especially in the topsoil layers. A particularly wide range of dehydrogenase and urease activity was obtained in the soil sown with the white mustard catch crop. The other catch crops (lacy phacelia and faba bean + spring vetch) also stimulated enzymatic activity. The obtained results show the positive role of catch crops and conservation tillage in bringing about positive changes occurring in the soil environment.

Keywords: catch crops; plough tillage; conservation tillage; monoculture; soil physical composition; soil enzymatic activity

1. Introduction

Cereal monocultures cause many adverse soil environment changes. We can observe this effect independently of the adopted cultivation system [1,2]. Plough tillage is replaced more and more frequently by conservation tillage, and this process takes place in many countries [3–5]. Succession planting (including cover cropping) generally modifies to a small extent soil physical properties. Soil physical properties are of great importance for agricultural production and sustainable use of agricultural land [6] because they are fundamental for some essential chemical and enzymatic processes occurring in soil or can even be a determining factor in this respect. For instance, water infiltration, soil aeration, and root penetration are all determined by soil structure [6,7]. Catch crops (organic matter) incorporated into soil increase soil C and N content and soil moisture content [8]. Catch crops contribute, among others, to decreased soil bulk density. The cultivation of catch crops decreases soil compaction in the 0–10 cm soil layer and increases the compaction in the 10–20 cm layer [9]. Tillage systems, from conventional ploughing to greatly reduced tillage, significantly influence soil physical, chemical, and biological properties [10,11]. The proper selection of a tillage system predominantly depends on local soil conditions, climate, and crop type [12–15]. Biological processes determining soil productivity and fertility are primarily associated with microbes and the enzymes released by them [16,17]. Monitoring of the pedosphere, using methods based on enzymatic testing, allows us to perform a comprehensive evaluation of changes occurring in the soil environment under the influence of various tillage systems [18,19]. According to Gianfreda et al. [20] and Gil-Sotres et al. [21], dehydrogenases are enzymes that inform us about the state of the environment and the microbiological activity of soil. Some researchers use dehydrogenase activity to assess soil quality and the effect of soil use on soil quality, but it can also be used to estimate the degree of remediation of degraded soils. On the other hand, many authors report that urease activity should be used as a soil quality indicator as well as an indicator for changes taking place in soil as affected by its use [21,22]. Soil enzymatic activity is an essential parameter because it reveals the state of the natural environment and shows biochemical processes taking place in it. It also reflects to what degree and extent the environment is polluted [23].

This study hypothesized that the utilization of phytosanitary, structure-forming, and allelopathic effects of catch crops, in combination with reduced (conservation) tillage, would contribute to an improvement in some physical parameters of loess soil and its enzymatic activity. This study aimed at assessing the regenerating effect of specific catch crop species and two tillage systems (plough tillage and conservation tillage) on the physical properties of soil and its enzymatic activity.

2. Methods

A field experiment on the cultivation of spring wheat in monoculture (cv. 'Monsun') was established in 2013, whereas the research results included in this work were collected over the period 2014–2016 (three-year monoculture). The experiment was established at the Czesławice Experimental Farm, belonging to the University of Life Sciences in Lublin (Poland), on loess soil with the grain size distribution of silt loam (PWsp) and categorized as good wheat soil complex (soil class II). In the year in which the experiment was set up, the soil humus content was 1.44%, pH = 6.2, while the P, K, and Mg content were, respectively, 160, 284, and 64 mg kg^{-1} soil. The experiment was set up as a split-plot design with five replicates in plots with an area of 27 m^2. The design of the experiment comprised two factors: I. Type of catch crop in a spring wheat monoculture: A—control treatment (without catch crop); B—white mustard (cv. 'Borowska'); C—lacy phacelia (cv. 'Stala'); and D—faba bean + spring vetch (cv. 'Amulet' + cv. 'Hanka'). II. Tillage practices used after harvest of the spring wheat and before sowing of the catch crops, and subsequently, tillage practices after harvest of the catch crops and before sowing the cereal crop:

1. Conventional plough tillage—after harvest of the spring wheat crop (first 10 days of August), wheat straw was removed from the field, subsoil ploughing and harrowing were carried out, and subsequently, the catch crops were sown (second 10 days of August); after the harvest of the catch crops (October), their aboveground biomass was shredded and incorporated into the soil during autumn ploughing; and in the spring, a tillage unit was used, mineral NPK fertilization was applied, and spring wheat was sown by seed drill (second 10 days of April), (Table 1).

2. Conservation tillage—after harvest of the spring wheat crop (first 10 days of August), wheat straw was removed from the field, the field was tilled with a rigid tine cultivator (grubber), and the catch crops were sown (second 10 days of August); after the harvest of the catch crops (October), their aboveground biomass was shredded and left in the field as mulch (until 15 March); and in the spring, the mulch was incorporated into the soil using a disk harrow, the field was smoothed with a spike tooth harrow, mineral NPK fertilization was applied, and spring wheat was sown a seed drill with disks (second 10 days of April).

Table 1. The design of agronomic operations related to the cultivation of catch crops and spring wheat.

Date of Performance	Plough Tillage	Conservation Tillage
First 10 days of August	Harvest of spring wheat (stubble left in the field; straw removed from the field)	Harvest of spring wheat (stubble left in the field; straw removed from the field)
Second 10 days of August	Field preparation for sowing catch crops (subsoil ploughing, harrowing), sowing of catch crops	Field preparation for sowing catch crops (no-tillage)—rigid tine cultivator (grubber), harrowing
Second 10 days of October	Catch crop biomass is cut and then shredded. Incorporation of biomass into the soil (ploughing-in of biomass)	Catch crop biomass is cut and then shredded. Biomass is left on the field surface (mulch)
Third 10 days of October—First 10 days of April	Catch crop biomass mixed with the soil decomposes into organic matter	Catch crop biomass left in the field (mulch) slowly decomposes
Second 10 days of March—Second 10 days of April	Field preparation for sowing spring wheat (tillage practices as in plough tillage)	Field preparation for sowing spring wheat (tillage practices as in conservation tillage)

In all treatments, mineral NPK fertilization was applied (adjusted to the requirements of the spring wheat and individual catch crop species). Based on the availability of the major macronutrients in the soil used in the experiment and taking into account "economical" crop protection to be used, the following rates of mineral fertilizers (kg ha^{-1}) were applied for the individual crops included in the field experiment: spring wheat (N—60, P_2O_5—50, K_2O—80), white mustard (N—40), lacy phacelia (N—40), and faba bean + spring vetch (N—40).

During the experimental years, spring wheat was sown at the optimal agronomic time for the region (second 10 days of April at a rate of 200 kg ha^{-1}). The sowing of catch crops was carried out in the second 10 days of August in each year. The seeding rate was as follows, respectively: white mustard −20 kg ha^{-1}, lacy phacelia −5 kg ha^{-1}, and faba bean + spring vetch −100 + 40 kg ha^{-1}.

In order to determine the comprehensive effects of catch crops on the crop stand, soil samples were taken from the 0–20 cm layer, and the selected soil physical parameters were analyzed. Soil samples were taken using a soil sampling tube from an area of 0.20 m^2 in each plot in the spring period (before spring wheat was sown).

Soil particle size fraction was determined by the sedimentation method, which is based on Stoke's Law and comprises, among others, the areometric method—in Poland it is most frequently used under the name of the Casagrande method with Prószyński's modification. Soil moisture content and bulk density as well as total and capillary porosity in the layers of 5–10 and 15–20 cm were determined in two replicates per plot using a 100 cm^3 cylinder. Soil total porosity was determined by the pycnometric method. Soil capillary porosity was established by capillary infiltration method. Soil compaction was examined using an electronic probe (penetrometer) in the 0–30 cm layer, every 5 cm in five replicates per plot. To evaluate the water stability of soil aggregates, the soil samples were wet sieved using screens with different mesh sizes (0.25, 0.5, 1, 3, 5, 7, and 10 mm) in the Baksheiev apparatus. Determinations were made in three replicates and subsequently the mean weight diameter of aggregates (MWDg) and the water stability index of soil aggregates (Wo) were calculated according to the following formula:

$$\mathrm{Wo} = \frac{\text{The total fraction of wet sieved aggregates without the fraction} < 0.25\ \text{mm}}{\text{The total fraction of dry sieved aggregates without the fraction} < 0.25\ \text{mm}} \times 100\%$$

To determine enzymatic activity, fresh soil samples with natural moisture content were collected. Samples were taken with a cylinder (100 cm^3) in triplicate in each plot. Dehydrogenase activity was determined using the method developed by Lenhard, which followed the Casida procedure, and it was expressed in µmol TPF kg^{-1} h^{-1} [22]. The determination of urease activity followed the Tabatabai and Bremner method [24], and this activity was expressed in mmol NH_{4+} kg^{-1} h^{-1} [22].

3. Statistical Analysis

Analysis of variance (ANOVA) was used to statistically analyze the results by employing Statistica PL 13.3, while Tukey's test was applied to determine HSD (Honest Significant Difference) values at $p < 0.05$. The mean for the study period is given in the results tables because the year-to-year differences between the characteristics analyzed were statistically insignificant. No significant interaction was found between the main experimental factors: A (tillage system) and B (catch crops), and also no significant three-factor (A × B × C) interaction was found between the main factors (A and B) and years (C). For the resulting data presented in Tables 4–9 the following were calculated: SD—standard deviation and CV—coefficient of variation.

4. Weather Conditions

The weather conditions during the catch crop growing season are shown in Tables 2 and 3. The presented data shows that the individual research period (2014–2016) was similar in terms of the sum of precipitation and average air temperatures. In each year of research, the amount of rainfall in August and September was higher than the long-term average, while in October it was lower than in many years. Air temperatures in August were slightly higher than the long-term average, while in September and October they were lower. Similar meteorological conditions in the years of the research probably resulted in statistically insignificant differences for all the result features analyzed in the paper.

Table 2. Total rainfall and rainfall distribution (mm) in Czesławice during the period 2014–2016 in the months of the catch crop growing season.

Specification	Month			Annual Total
	VIII	IX	X	
Monthly total in 2014	78.1	82.6	19.3	648.0
Monthly total in 2015	80.5	80.1	24.0	633.4
Monthly total in 2016	76.4	78.4	21.7	666.2
Long-term mean (1966–2002)	68.2	56.9	49.2	612.6

Table 3. Mean air temperatures (°C) in Czesławice during the period 2014–2016 in the months of the catch crop growing season.

Specification	Month			Annual Mean
	VIII	IX	X	
Monthly mean in 2014	19.3	11.2	5.8	7.5
Monthly mean in 2015	18.9	10.9	6.1	7.7
Monthly mean in 2016	19.5	11.4	5.6	8.0
Long-term mean (1966–2002)	17.7	13.3	8.4	7.8

5. Results

The catch crop caused differences in the particle size distribution of the soil that was used in the present experiment (Table 4).

Relative to the control, all the catch crops caused a reduction in the percentage of the fraction of soil aggregates with a size of 1.0–0.1 mm and the 0.1–0.02 mm fraction as well as an increase in the percentage of the fine and finest fractions (0.02–0.002 mm and <0.002 mm), regardless of tillage system. It is worth noting that the lowest percentage of the largest particle size fractions and, at the same time, the highest percentage of the fine fraction were provided by growing the mixed legume crop. Regardless of catch crops, conservation tillage slightly differentiated the soil particle size distribution, resulting in an increased percentage of the larger fractions. However, the introduction of catch crops in this tillage treatment contributed to an improvement in the particle size distribution (in particular, a rise in the percentage of the 0.02–0.002 mm fraction).

Table 4. Percentage of major particle size fractions (in %) in the soil used in the experiment—on average over the study period.

Treatment	Tillage System							
	Plough Tillage				Conservation Tillage			
	Soil Particle Size Fractions (mm)							
	1.0–0.1	0.1–0.02	0.02–0.002	<0.002	1.0–0.1	0.1–0.02	0.02–0.002	<0.002
A *	5 a **	54 a	33 a	8 a	9 b	57 b	29 b	5 b
B	4 a	51 a	36 a	9 a	7 b	55 b	32 b	6 b
C	4 a	52 a	35 a	9 a	8 b	56 b	30 b	6 b
D	3 a	50 a	37 a	10 a	7 b	53 b	33 b	7 b
$HSD_{(0.05)}$	0.6	1.9	1.8	0.7	0.7	1.8	1.7	0.6

$HSD_{(0.05)}$ for years—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences

* A–D—explanation in the Methods section; ** a,b—average values of individual soil fractions (between plough tillage and conservation tillage) within a row followed by various letters are significantly different ($p < 0.05$).

In comparison with plough tillage, conservation tillage reduced the volumetric soil moisture content, but in the soil layer of 5–10 cm, these differences were statistically insignificant, whereas in the 15–20 cm layer, they were about 17% (Table 5).

Table 5. Soil moisture content (in % volume) and the water stability index (in %) of the soil structure—on average over the study period.

Specification	Soil Moisture Content		Water Stability Index (Wo)
	In 5–10 cm Layer	In 15–20 cm Layer	
PT *	17.9 ±1.1 ***	18.7 ±1.2	50.2 ±9.0
CT	17.1 ±1.0	15.5 ±0.8	59.9 ±9.9
CV (%) ****	4.2	8.7	4.5
$HSD_{(0.05)}$	n.s *****	1.45	n.s.
A **	16.7 ±0.9	16.9 ±0.8	40.4 ±9.3
B	18.0 ±0.6	17.1 ±0.5	60.0 ±7.2
C	17.7 ±0.8	16.9 ±0.8	50.4 ±7.6
D	17.6 ±0.7	18.2 ±0.4	70.2 ±8.1
CV (%)	6.7	7.1	8.5
$HSD_{(0.05)}$	1.28	1.22	12.2

$HSD_{(0.05)}$ for years—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences

* PT—plough tillage, CT—conservation tillage; ** A–D—explanation in the Methods section; *** SD—standard deviation; **** CV—coefficient of variation; ***** n.s.—not significant differences.

Among the cover crops included in the experiment, only white mustard significantly affected the soil moisture content on a volume basis in the 5–10 cm layer compared to the control treatment. The other catch crops caused only a slight rise in the soil moisture content in the 5–10 cm layer. In the deeper (15–20 cm) soil layers, the effect of the catch crops on the soil moisture content was marginal, except for the legume cover crop (Table 5). Regarding the soil under spring wheat, the water stability index of the soil structure was modified by both experimental factors. Conservation tillage resulted in better (albeit statistically insignificant) water aggregate stability compared to conventional (plough) tillage. The introduction of catch crops into the monoculture cultivation of spring wheat was advisable in terms of soil water stability. In this respect, the white mustard and mixed legume catch crops proved to be especially useful (Table 5). It was found that in the 5–10 cm layer, the soil bulk density in plough tillage was substantially higher by nearly 10% in comparison with conservation tillage. The catch crops also modified significantly this parameter—growing mixed legumes contributed to a lower soil bulk density in the 5–10 cm layer (by 5% on average) in comparison with the control plots (without catch crop). The soil bulk density in the 15–20 cm layer was also smaller on objects with catch crops in comparison with the control plots (without catch crop). A statistically significant decrease in this parameter resulted in the cultivation of the mixture (faba bean + spring vetch) and lacy phacelia. On the other hand, conservation tillage resulted in a statistically proven decrease in the soil bulk density by about 9% in relation to conventional tillage (Table 6).

Table 6. Soil bulk density (in g cm^{-3})—on average over the study period.

Specification	Soil Bulk Density	
	In 5–10 cm Layer	In 15–20 cm Layer
PT *	1.61 ±0.033 ***	1.65 ±0.031
CT	1.46 ±0.022	1.50 ±0.020
CV (%) ****	9.7	11.6
$HSD_{(0.05)}$	0.052	0.064
A **	1.56 ±0.019	1.62 ±0.024
B	1.55 ±0.021	1.59 ±0.029
C	1.53 ±0.024	1.57 ±0.025
D	1.50 ±0.025	1.53 ±0.028
CV (%)	9.0	10.3
$HSD_{(0.05)}$	0.041	0.050
$HSD_{(0.05)}$ for years—not significant differences		
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—not significant differences		
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences		

* PT—plough tillage, CT—conservation tillage; ** A–D—explanation in the Methods section; *** SD—standard deviation; **** CV—coefficient of variation.

A consequence of the lower soil bulk density under conservation tillage conditions was an increase in the total soil porosity in both soil layers considered (5–10 cm and 15–20 cm). Under plough tillage, the total soil porosity was found to be significantly lower (by 8% in the 5–10 cm layer and by 9% in the 15–20 cm layer). The catch crops (especially legume mixture) significantly increased the total soil porosity, regardless of tillage system (Table 7). The conventionally tilled soil (plough tillage) in the spring wheat monoculture was characterized by a lower number of capillaries at both depths examined by 11.6% relative to conservation tillage. The catch crops were not found to have a significant effect on changes in soil capillary porosity in both layers analyzed (Table 7).

Soil compaction in all layers investigated depended significantly on tillage system. The use of conservation tillage in the spring wheat monoculture resulted in a distinct reduction in soil compaction in comparison with conventional tillage. The greatest difference was observed in the 15–20 cm and 20–25 cm layers, which was 64.7% (Table 8). Catch crops affected to a smaller extent the variation in soil compaction. However, the study found the soil compaction in the shallower soil layers (0–5 cm, 5–10 cm, and 10–15 cm) to decrease, especially under the influence of legume catch crop (statistically significant difference from control plots—without catch crops). The catch crops also contributed to the reduction of soil compaction in deeper soil layers, but the differences were not statistically significant (Table 8).

The activities of the enzymes analyzed exhibited significant differences depending on tillage system. The highest dehydrogenase and urease activity was found under conservation tillage, in particular in the surface (5–10 cm) soil layers (Table 9).

Table 7. Soil total porosity (in %) and soil capillary porosity (in %)—on average over the study period.

Specification	Soil Total Porosity		Soil Capillary Porosity	
	In 5–10 cm Layer	In 15–20 cm Layer	In 5–10 cm Layer	In 15–20 cm Layer
PT *	38.3 ±1.4 ***	36.5 ± 1.5	32.8 ± 1.0	30.9 ± 0.8
CT	41.8 ±2.1	40.1 ± 1.9	36.6 ± 2.3	34.5 ± 1.2
CV (%) ****	11.9	11.3	11.7	11.1
$HSD_{(0.05)}$	1.324	1.513	1.721	1.504
A **	38.5 ± 1.5	36.4 ± 2.1	34.4 ± 0.8	32.4 ± 0.6
B	40.2 ± 0.9	38.2 ± 1.2	34.7 ± 0.8	32.8 ± 0.8
C	40.1 ± 0.6	38.7 ± 2.0	34.6 ± 0.9	32.5 ± 0.5
D	40.7 ± 1.0	39.1 ± 0.6	35.0 ± 1.1	33.0 ± 0.9
CV (%)	10.9	12,8	4.9	4.7
$HSD_{(0.05)}$	1.294	1.476	n.s. *****	n.s.

$HSD_{(0.05)}$ for years—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences

* PT—plough tillage, CT—conservation tillage; ** A–D—explanation in the Methods section; *** SD—standard deviation; **** CV—coefficient of variation; ***** n.s.—not significant differences.

Table 8. Soil compaction (MPa)—on average over the study period.

Specification	Soil Layer (cm)						
	0–5	5–10	10–15	15–20	20–25	25–30	0–30
PT *	0.55 (±0.04) ***	1.48 (±0.06)	2.13 (±0.11)	2.47 (±0.17)	2.80 (±0.19)	3.11 (±0.07)	2.09 (±0.02)
CT	0.39 (±0.02)	1.18 (±0.07)	1.41 (±0.14)	1.50 (±0.12)	1.70 (±0.11)	2.09 (±0.09)	1.38 (±0.06)
CV (%) ****	16.3	20.1	20.4	40.7	46.8	25.3	17.0
$HSD_{(0.05)}$	0.044	0.115	0.153	0.112	0.164	0.316	0.052
A **	0.56 (±0.02)	1.45 (±0.06)	2.12 (±0.10)	1.54 (±0.14)	1.77 (±0.15)	2.26 (±0.08)	1.62 (±0.07)
B	0.54 (±0.01)	1.42 (±0.02)	2.10 (±0.09)	1.49 (±0.16)	1.72 (±0.16)	2.11 (±0.03)	1.56 (±0.08)
C	0.54 (±0.02)	1.40 (±0.05)	2.08 (±0.13)	1.50 (±0.13)	1.71 (±0.12)	2.13 (±0.04)	1.56 (±0.03)
D	0.38 (±0.04)	1.17 (±0.08)	1.39 (±0.15)	1.46 (±0.08)	1.68 (±0.10)	2.06 (±0.06)	1.36 (±0.04)
CV (%)	15.3	19.7	19.9	5.1	4.9	5.2	10.4
$HSD_{(0.05)}$	0.045	0.092	0.164	n.s. *****	n.s.	n.s.	0.075

$HSD_{(0.05)}$ for years—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—ot significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences

* PT—plough tillage, CT—conservation tillage; ** A–D—explanation in the Methods section; *** SD—standard deviation; **** CV—coefficient of variation; ***** n.s.—not significant differences.

On average, the conservation tillage system resulted in a 23.5% (5–10 cm soil layer) and 19.1% (15–20 cm soil layer) higher dehydrogenase activity, and a 25.6% (5–10 cm soil layer) and 22.5% (15–20 cm soil layer) higher urease activity. Catch crops significantly influenced soil enzymatic activity. Significantly, the control treatments (without catch crop) were found to have the lowest dehydrogenase and urease activity in both the 5–10 cm and 15–20 cm layers. This confirms the positive effect of catch crops on the state of the soil environment. Among the catch crops, white mustard had the most beneficial effect on dehydrogenase and urease activity.

Table 9. Soil enzymatic activity—on average over the study period.

Specification	Dehydrogenase Activity (μmol TPF kg^{-1} h^{-1})		Urease Activity (mmol NH_4^+ kg^{-1} h^{-1})	
	In 5–10 cm Layer	In 15–20 cm Layer	In 5–10 cm Layer	In 15–20 cm Layer
PT *	5.1 ±0.12 ***	4.7 ±0.08	4.3 ±0.10	4.0 ±0.06
CT	6.3 ±0.14	5.6 ±0.05	5.4 ±0.09	4.9 ±0.07
CV (%) ****	19.3	15.7	16.2	11.4
$HSD_{(0.05)}$	0.9	0.7	0.6	0.5
A **	4.8 ±0.11	4.5 ±0.05	4.2 ±0.09	3.9 ±0.04
B	6.6 ±0.17	5.8 ±0.07	5.8 ±0.12	5.2 ±0.03
C	5.9 ±0.15	5.3 ±0.09	5.3 ±0.14	4.7 ±0.07
D	6.1 ±0.13	5.5 ±0.06	5.5 ±0.12	4.9 ±0.08
CV (%)	30.3	21.2	22.4	25.3
$HSD_{(0.05)}$	0.8	0.6	0.7	0.5

$HSD_{(0.05)}$ for years—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops)—not significant differences
$HSD_{(0.05)}$ for interaction (tillage system × catch crops × years)—not significant differences

* PT—plough tillage, CT—conservation tillage; ** A–D—explanation in the Methods section; *** SD—standard deviation; **** CV—coefficient of variation.

6. Discussion

When incorporated into the soil, catch crop biomass enhances the intensity of microbiological processes and enzymatic activity, becoming the organic matter precursor. The ploughing-in of catch crops results in a change in the soil physicochemical properties [19,25–27]. Soil moisture content is particularly important in growing cereals. Some studies showed an increase in soil moisture in cereal monoculture when white mustard catch crop and tansy phacelia were included in the crop [9,28,29]. It should be noted that the catch crops stimulated a higher soil moisture content only in the topsoil layer (0–10 cm), while their impact on the moisture content in the deeper layers proved to be insignificant [30,31]. Catch crops with deep roots are particularly effective in enhancing soil-water storage capacity [32,33].

Organic substance is glue that aggregates soil particles. Organic matter has been shown [34–37] to have a positive impact on the formation of soil aggregates and their stability. This study confirmed that the soil structure indicators and soil aggregate water stability change under the influence of catch crops. The effect of a catch crop on the soil pulverization index depends on the species cultivated [38,39]. Favorable values of this indicator (similar to our own research) are observed, for example, after the cultivation of tansy phacelia [29]. In the present study, the incorporation of catch crop biomass into the soil (direct incorporation into the soil—plough tillage, or as slowly decomposing mulch—conservation tillage) contributed to beneficial changes in some soil physical parameters compared to the plots without catch crops. A clearly positive effect of the legume mixture is due to the well-developed root system of these plants and their high aboveground biomass yield. Catch crop biomass contributed to the formation of soil organic matter, which in turn induced greater soil loosening (soil bulk density, soil total porosity, and soil compaction) and enabled better water storage in the soil (water stability index and soil moisture content). Furthermore, catch crop biomass beneficially affected soil enzymes, whose activity is positively correlated with soil organic matter content. After catch crops are introduced into agronomic practices, the soil compaction decreases by about 18%–20% (in the 5–10 cm layer) [6,31]. Organic matter increases soil porosity and promotes macropore formation. In the opinion of Głąb and Kulig [40], catch crops decreased bulk density to 1.25 g cm^{-3} at a depth of 0–10 cm and increased macropore size by as much as 125.5%, but only in the treatment with reduced tillage. Catch crops play an important role in compact soils in simplified tillage systems by increasing total porosity and decreasing the bulk density [40] of soil, which can be attributed to higher C content and higher soil biological (enzymatic) activity [41].

Analyzing the results of our own research, we note that conservation tillage increases the total and capillary soil porosity. However, soil bulk density and soil compaction decreased. Similar observations regarding the effect of no-tillage on soil physical properties have also been found by other authors [8,38]. The relationships and the order of magnitude of soil physical parameters analyzed, which were found by de Cima et al. [42] are similar to those determined in this research. In the cited study, soil water content ranged from 15.2% to 19.8%, dry bulk density ranged from 1.39 to 1.60 mg m^{-3}, and total porosity ranged from 38.7% to 46.5%. Catch crops left in the field as mulch increased the moisture content of soil by inhibiting surface runoff, improving infiltration, and decreasing evaporation [43], which is confirmed by this research.

In the present study, enzymatic tests confirmed the positive effect of conservation tillage and catch crops on soil enzymatic activity. Bielińska et al. [11] and Bielińska and Mocek-Płóciniak [19] also prove that tillage reductions stimulate the activity of soil enzymes, in particular dehydrogenases. According to the authors quoted above, similarly to the present study, soil enzymatic activity was higher in the shallower soil layers. Catch crop biomass (ploughed in or left as mulch) is, among others, an important source of soil organic matter that enhances soil enzyme activities [2,20,21,44]. Other authors [9,45–48] also note that high soil enzymatic activity is conditional on the absence of ploughing and on soil coverage by plants throughout the entire growing season (or its major part). Catch crops improve soil moisture and thermal conditions, while these, in turn, determine soil enzymatic activity [49]. Increased soil water content significantly impacts the level of dehydrogenase activity [45]. In our own research, the activity of soil enzymes significantly increased under the influence of the fertilizing effect of biomass from catch crops. Antonkiewicz et al. [50] also proved that the activity of the studied enzymes increased with increasing the dose of fertilization introduced into soils, which was associated with the amount of carbon substrates available for microorganisms and enzymes. The type of enzyme is a determining factor for the direction and intensification of observed changes, which is related both to the content of specific substrates as regards soil enzymatic responses as well as to enzyme-specific sensitivity and resistance to environmental factors [23,51].

7. Conclusions

Catch crops caused a variation in the soil particle size distribution, resulting in a higher percentage of the finer soil fractions. Moreover, the catch crops (especially the legume mixture) had a beneficial effect on the soil bulk density and soil total porosity (in the 5–10 cm and 15–20 cm layer) and soil compaction in the shallower soil layers (below 15 cm). Conservation tillage contributed to a significant decrease in soil bulk density and soil compaction as well as to an increase in soil total porosity and soil capillary porosity.

The soil moisture content in the spring wheat monoculture was significantly dependent on both tillage system and catch crops. Conventional (plough) tillage contributed to improved soil moisture content in the 15–20 cm layer. The catch crops stimulated an improvement in the moisture content in the shallower soil layers (5–10 cm), regardless of the tillage system used, and had an effect on higher water stability of the soil structure.

Conservation tillage stimulated significantly the activity of the soil enzymes analyzed (dehydrogenases and urease) both in the topsoil and in the deeper soil layers. Regardless of the tillage system, the catch crops (in particular white mustard) significantly positively affected soil enzymatic activity, improving soil environment quality.

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