Original Research

Effects of Various Long-Term Tillage Systems on Some Chemical and Biological Properties of Soil

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Abstract

One of the directions of actions limiting the occurrence in soil environments of unfavorable phenomena accompanying conventional tillage is the introduction of reduced tillage, even total abandonment of cultivation operations. The objective of the performed investigation was to compare the impact of conventional tillage, reduced tillage, and no-tillage on some soil chemical ($C_{org.}$, total N, pH) and microbiological (total bacterial counts, numbers of oligotrophs, copiotrophs and fungi, activity of dehydrogenases and acid phosphatase) properties.

Studies carried out in 2010-12 involved a static field experiment initiated in 1999 at Brody Research Station of Poznań University of Life Science, Poland, in temperate climate, on a soil classified as Albic Luvisols developed on loamy sands overlying loamy material. Analyses were performed on soil samples collected from under winter wheat from two horizons: 0-10 cm and 10-20 cm.

In the 0-10 cm layer, the lowest values of almost all analyzed indices ($C_{org.}$, total N, total bacterial counts, numbers of oligotrophs, copiotrophs and fungi, as well as the activity of dehydrogenases and acid phosphatase) were determined in conditions of conventional tillage. In the 0-10 cm soil layer, in all years of study, the highest numbers of bacteria were found in conditions of reduced tillage and no-tillage. On the other hand, in the course of the remaining years of study, the most numerous bacterial counts in the 10-20 cm soil layer were determined in conditions of conventional tillage. More interesting conclusions were arrived at following the analysis of soil bacteria after splitting them into oligotrophic. Numbers of oligotrophs in individual experimental combinations were found to be distributed in a way similar to total bacteria counts.

Keywords: enzymatic activity of soil, soil microorganisms, soil erosion, tillage systems

Introduction

The effect of management practice on soil properties may provide essential information for assessing environmental impact. Continual soil inversion, using tools such as the plough, lead directly and indirectly to environmental problems. Arable fields are more vulnerable to soil erosion and loss of organic matter. The erosion of cultivated soils that results from the action of wind and water leads to a loss of nutrients, pesticides, and pollution from eutrophication

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and sedimentation of rivers and streams. Non-inversion tillage, known as "conservation tillage" has been found to be successful in reducing soil erosion [1, 2].

In all areas where soil protection against erosion or degradation is of prime importance (for example, in areas with deficiency of rainfall) and there is much of that in Poland [3], careful consideration should be given to possibilities of the application of no-tillage systems.

Recent interest in maintaining soil quality has been stimulated by a renewed awareness of the importance of soil conditions to both the sustainability of agricultural production systems and environmental quality [4]. Conservation agriculture is now widely recognized as a viable concept for sustainable agriculture. The basic elements of conservation agriculture are: very little or no soil disturbance, direct drilling into previously untilled soil, crop rotation, and permanent soil cover. By changing the soil tillage system from ploughing to reduced tillage or direct drilling, nearly all physical, chemical, and biological properties of the soil may be affected [1, 5, 6]. Biological, physical, and chemical processes continually interact with time, resulting in a diversely arranged mixture of soil minerals, organic matter, and pore spaces that together define soil structure [7]. Research has demonstrated the potential of ploughless tillage, especially of no-tillage, for improved soil nutrient recycling [8].

The reduction of soil disturbance decreases mineralization of soil organic matter and it can result in larger conservation soil organic C [9-11]. It has been conferred that tillage may expose protected organic matter that may serve as a substrate for microbial growth [12]. In general, the long-term effects of non-inversion tillage on the population and activity of the microbial have been closely related to soil organic content, whereas short-term effects are more complex and also depend on soil conditions such as soil texture, climate, cropping system and the type of crop residue [9, 13].

Soil biological properties are critical to soil sustainability and are important indicators of soil quality. Therefore, such indicators have the potential to serve as early signals of soil degradation or soil improvement [14-17]. Soil microorganisms play integral roles in nutrient cycling, soil stabilization, and organic matter decomposition. Generally, adoption of continuous reduced tillage and no-tillage for several years has led to increased organic C, soil microbial biomass and the activity of several enzymes in the surface layers compared with the ploughing system [2, 11, 18, 19].

By understanding the effects of tillage on soil biological properties, management systems can be implemented that improve natural nutrient cycling processes, resulting in increased agricultural sustainability of ecosystems [20].

The objective of this study was to determine the effects of the 13-year ploughless tillage systems on some chemical and microbial properties. Results were compared to those obtained under conventional tillage. We hypothesized that reduced tillage and no-tillage would have a positive effect by increased organic C and soil fertility and enhancing soil microbial functionality.

Experimental Procedures

The studies carried out over 2010-12 involved a static field experiment initiated in 1999 at Brody Research Station at Poznan University of Life Science, Poland (52º26'N, 16º17'E), on a soil classified as Albic Luvisols developed on loamy sands overlying loamy material. The organic C was 8.1 $g\cdot kg^{-1}$ determined by the Tiurin method – K dichromate oxidation, and pH value measured in 1 M KCl with the potentiametric method had 6.5 [21]; available contents of P and K are 207 and 119, respectively, according to Egner-Riehm method [22], and 32 $mg\cdot kg^{-1}$ of Mg according to Schachtschabel method [21]. Winter wheat cultivar Turkis was grown in a 4-year rotation: pea, winter wheat, spring barley, winter triticale. The sowing rate was 500 seeds per 1 m^2. Three tillage systems were arranged in a randomized block design in four replications. The tillage systems consisted of:

1) conventional tillage with mouldboard ploughing in autumn to a normal depth (25 cm), followed by seed bed preparation and sowing (CT)
2) reduced tillage to a maximum depth of 10 cm with shallow stubble cultivator (RT)
3) no-tillage – no pre-planting mechanical seedbed preparation (NT)

In reduced tillage and no-tillage systems, planting was executed by means of a disc coulter drill from the Great Plains Company. Fertilization was uniform for all tillage systems and each experimental year (120 kg $N\cdot ha^{-1}$, 35 kg $P\cdot ha^{-1}$, 66 kg $K\cdot ha^{-1}$). The herbicide program for tillage systems used pre-plant emergence applications. Before planting, 3 $dm^3\cdot ha^{-1}$ of glyphosate herbicide was applied on all plots with no-tillage and reduced tillage to control perennial weed and volunteers. For weed control during the growing season pre-emergence Legato Plus 600 SC herbicide was applied at the rate of 1.4 $l\cdot ha^{-1}$. The seeds were dressed with Raxil Extra 060 FS fungicide (60 ml per 100 kg seeds). For disease control Falcon 460 EC at the rate of 0.6 $l\cdot ha^{-1}$ was applied on all plots at BBCH 31 growth stage.

Soil samples for chemical analyses were collected after harvest of winter wheat in 2010. The replication plot was represented by a mean sample consisting of 10 individual samples collected using an Egner sampler from the 0-10 cm and 10-20 cm layer. After drying, the soil was crushed by hand and sieved through a 2-mm sieve. Organic carbon was determined by the Tiurin oxidation method, total N by Kjeldahl method, and pH in 1 mol $KCl\cdot dm^3$ [21].

Soil samples for biological analyses were collected in heading growth stage of winter wheat (BBCH 56-58) in each years in the same way as the samples for chemical analyses.

The number of microorganisms was determined by the plate method according to Koch on adequate agar substrates (in 4 replications) [23]. The mean number of colonies was converted into soil dry matter on the basis of the amount and moisture of the soil sample. Next, the degree of dilution of the supernatant obtained from the soil also was considered.

Table 1. Mean daily temperatures of air and sum of precipitation in spring vegetation period of winter wheat in 2010-12 and 1961-2010.

Year	Vegetation period					Mean or sum
	March	April	May	June	July	
Mean temperatures (ºC)						
2010	4.4	10.0	12.5	18.7	21.6	13.4
2011	3.1	11.7	14.1	18.6	17.9	13.1
2012	5.7	8.8	14.8	16.0	19.2	12.9
1961-2010	2.9	7.9	13.2	16.6	18.2	11.8
Sum of precipitation (mm)						
2010	56.3	38.9	92.7	17.0	98.2	303.1
2011	25.0	13.9	34.0	52.6	175.4	300.9
2012	20.0	22.9	77.2	163.0	197.6	480.7
1961-2010	40.4	38.0	57.4	61.8	77.5	275.1

- Total bacteria counts were determined on a ready-to-use Merck-Standard count agar medium following 5 days of incubation at 25ºC [24].
- Oligotrophic bacteria (CFU·g^{-1} d.m. soil) were counted on diluted nutritive broth at 28ºC after 21 incubation days [25].
- Copiotrophic bacteria (CFU·g^{-1} d.m. soil) were determined on nutritive broth at 28ºC after 7 days of incubation [25].
- Fungi (CFU·g^{-1} d.m. soil) were counted on Martin's nourishing substrate at 24ºC [26].

The performed examination of the soil enzymatic activity in conditions of different tillage systems was based on the determination of the activities of dehydrogenase and acid phosphatase (in four replications).

The activity of dehydrogenases was identified by spectrophotometric method, using as substrate 1% TTC (triphenyl-tetrazole chloride), after 24-hour incubation in 30ºC, at 485 nm wavelength. Enzyme activity was expressed in µmol TPF·kg^{-1} DM of soil·24h^{-1} [27].

The activity of acid phosphatase was determined using as substrate p-nitrophenylophosphate sodium, after one hour incubation at 37ºC with 400 nm wavelength. Enzyme activity was expressed in µmol PNP·g^{-1} DM of soil·h^{-1} [28].

The results were tested by using standard variance analysis (ANOVA) for the randomized complete block. Mean separations were made for significant effects with LSD and Tukey tests at the probability of $P \leq 0.05$. Pearson correlation coefficient between chemical and biological properties were performed. All statistical analyses were carried out using software Statistica 7.1.

Results and Discussion

Weather Conditions

Mean air temperatures during the spring vegetation period of winter wheat (March-July) were higher than the 50-year mean, except in May 2010, in June 2012, and in July 2011 (Table 1). Precipitation in all years was higher in comparison to the 50-year mean. In 2012 the sum of precipitation was marginally higher, but in March and April a precipitation shortage occurred. In conclusion, weather conditions for spring growing season of winter wheat were least favorable in 2010 and 2012 and unfavorable in 2011.

Chemical Analysis of Soil

The results presented in Table 2 show that long-term application of a given tillage system modifies soil reaction only slightly. Soil pH is found to be affected to a much greater degree by such parameters as the content of organic carbon as well as total nitrogen, which are determined after harvest. It is worth emphasizing that in the surface layer of the soil profile (0-10 cm), these differences were stable and repeatable as indicated by their significance demonstrated with the assistance of statistical analysis. Tillage simplifications or its complete abundance contribute to a slight decline of soil pH and to a considerable increase in soil of organic carbon and nitrogen contents as well as to the elevation in the value of the C:N coefficient. All the above-mentioned parameters are characterized by a similar distribution, but the recorded differences are less conspicuous and statistically non-significant.

The determined values are characteristic for fertile arable lands. In the context of influencing soil site, its fertility, etc., the demonstrated differences in the soil reaction are so insignificant that it would not be a good idea to try to discern their impact on soil microbiological status. On the other hand, differences in values of the remaining parameters, in particular in the organic carbon content, can modify, to a significant extent, population numbers of soil microorganisms as well as soil enzymatic activity. However, it should be remembered that these are values determined after the harvest of plants in 2010. Although they are considered to be relatively stable, nevertheless temporary values, especially

Table 2. Chemical properties of soil under conventional tillage, reduced tillage, and no-tillage systems at different soil profile depths.

Parameter	Tillage systems	Soil layer	
		0-10 cm	10-20 cm
pH in 1 M KCl	Conventional tillage	6.69	6.71
	Reduced tillage	6.28	6.73
	No-tillage	6.23	6.74
	$LSD_{0.05}$	0.37	n.s.
Organic C ($g \cdot kg^{-1}$)	Conventional tillage	9.08	9.01
	Reduced tillage	11.84	8.97
	No-tillage	12.47	8.83
	$LSD_{0.05}$	0.62	n.s.
Total N ($g \cdot kg^{-1}$)	Conventional tillage	0.98	0.97
	Reduced tillage	1.19	0.94
	No-tillage	1.25	0.91
	$LSD_{0.05}$	0.12	n.s.
C:N	Conventional tillage	9.3	9.3
	Reduced tillage	9.9	9.5
	No-tillage	10.0	9.7
	$LSD_{0.05}$	0.31	n.s.

n.s. – non-sign.

those resulting from rapid supply of organic carbon in the form of after-harvest residues, etc., can differ from them and become more diverse in individual tillage systems as well as in different layers of the soil profile.

Microbiological Analysis of Soil

The picture of the influence of the examined factors on bacterial counts determined in the soil under wheat cultivation differed in individual layers of the soil profile and the observed differences were nearly always statistically significant (Fig. 1). In the 0-10 cm soil layer, in all years of study, the highest numbers of bacteria were found in conditions of reduced tillage and no-tillage. A favorable impact of the applied simplified tillage on total bacterial counts in this profile layer was particularly noticeable during the last year of investigation, when this parameter was found to be nearly two times higher than in the case of direct sowing and over five times higher in comparison with conventional tillage. In the same year, the applied tillage system was found to exert a similar influence also in the lower layer of the soil profile (10-20 cm). On the other hand, in the cource of the remaining years of study, the most numerous bacterial counts in the 10-20 cm soil layer were determined in conditions of conventional tillage. There is no doubt that this situation can be attributed to the relocation of considerable quantities of organic matter from post-harvest residues to deeper layers of the soil as a result of ploughing accompanied by improved aeration of these soil layers. This conclusion is further corroborated by the content of organic carbon (Table 2), whose quantities in the 10-20 cm soil layer were accumulated very effectively in conditions of traditional ploughing tillage.

The same reasons could probably explain one more particularly interesting relationship that was found to occur in all years of investigations, namely, while in both no-tillage systems, there were always more bacteria in the near-surface soil layer (0-10 cm) than in the deeper (10-20 cm) layer. In conditions of conventional (ploughing) tillage, the number of bacteria in the 10-20 cm layer was always slightly higher in comparison with the near-surface soil profile layer. It should be stressed here that trends regarding bacterial counts in individual soil layers found their statistically significant confirmation also in the mean values from the entire experimental period.

This situation differs significantly from the information repeated in numerous publications maintaining that the highest concentrations of microorganisms can be found in the surface soil layer [29, 30]. Roldán et al. [31] reported higher content of organic matter in the 0-5 cm soil layer, and this increased together with the intensity of tillage. The results of their experiments showed that the mean organic matter content in the examined surface layer of soil was by 32% higher in the no-tillage system in comparison with the ploughing system. One of many factors affecting the degree of growth and development of soil microorganisms is its organic matter content, since it provides energy and nutrients for them. Papers of Goberna et al. [32] or Song et al. [33] confirmed the decline in organic matter content together with the increase of the depth of the examined soil profile, the consequence of which was biomass reduction of microorganisms. However, the application of different tillage systems and, as a result, of different agrotechnical treatments, leads to relocation and, consequently, different distribution of the organic matter in the soil profile. Furthermore, conventional tillage causes increased supply of oxygen into deeper soil layers, leading to increased rates of organic matter mineralization following more intensive proliferation of microorganisms [34].

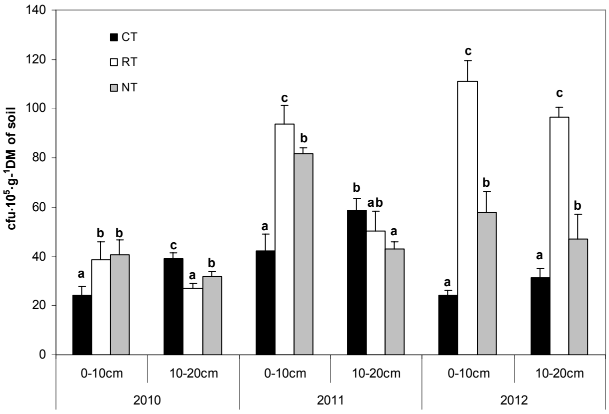

Fig. 1. Effects of tillage system on total bacteria counts in the two layers of the soil profile.

More interesting conclusions were arrived at following the analysis of soil bacteria after splitting them into oligotrophic and copiotrophic bacteria. Numbers of oligotrophs (Fig. 2) in individual experimental combinations were found to be distributed in a way similar to total bacteria counts. Their smallest quantities were determined in conditions of conventional tillage with the distance to reduced systems much more noticeable and occurring more regularly. Conservation tillage was found to be significantly better for oligotroph counts. Some literature data indicate that in the case of this group of enzymes, differences between the near-surface and deeper layers of the soil profile can be significantly greater – even several times [35, 36]. This correlation was most noticeable in the last year of experiments, which was characterized by high precipitation (Table 2).

The dependence of numbers of oligotrophic bacteria on soil profile level depths fully complied with the above-cited rules taken from appropriate literature sources (Fig. 2) and was found to decline with depth, irrespective of the applied tillage system.

Oligotrophs make up the majority of bacterial complexes inhabiting the soil, i.e. 80 to 85% of their total counts [37]. They exhibit quantitative dynamics characteristic for indigenous microflora, causing their numbers to remain at relatively stable levels. They process organic matter economically and show a negative response to excessively elevated concentrations of simple carbon compounds in the environment which, however, does not mean that their high proportions in soil indicate its poor fertility [37, 38].

On the other hand, copiotrophs are the type of bacteria whose development is preconditioned by appropriate supplies of fresh, easily-available organic matter, which is intensively mineralized by them. In contrast to indigenous oligotrophs, copiotrophic zymogens process organic matter in a very extravagant way, at high carbon losses, and their counts decline relatively rapidly after they use up easily available nutrient substrate [29, 39]. However, in the case of the current experiment, copiotrophs turned out to be a group of microorganisms characterized by the poorest size variability depending on both the applied method of tillage and the depth of soil profile (Fig. 3). Nevertheless, in the case of conventional tillage, copiotroph counts were always

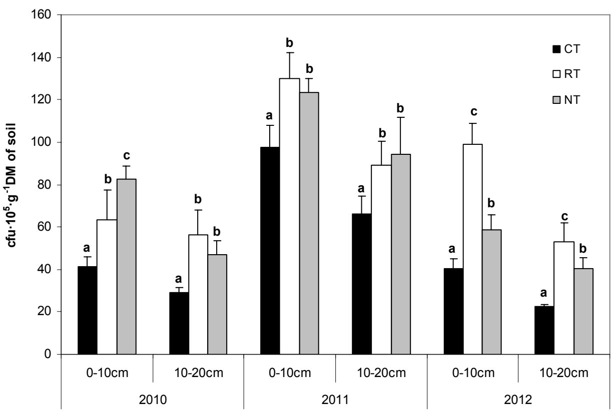

Fig. 2. Effects of tillage system on the oligotrophic bacteria counts in the two layers of the soil profile.

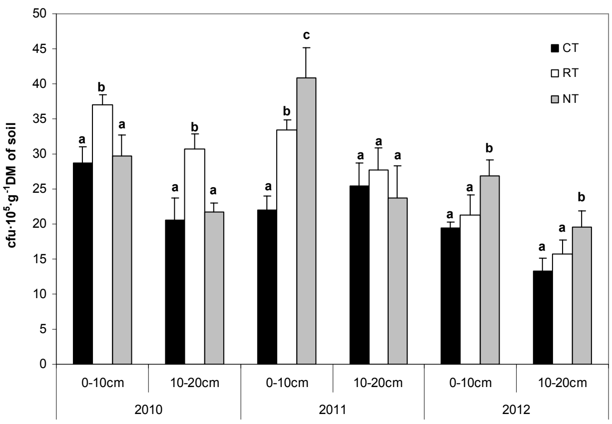

Fig. 3. Effects of tillage system on the copiotrophic bacteria counts in the two layers of the soil profile.

significantly lowest when compared with other tillage systems. In addition, in comparison with total bacterial counts and numbers of oligotrophs, differences in counts of copiotrophs were also lower in individual experimental years. Therefore, it can be said that they turned out to be a more stable group of microorganisms than oligotrophs, contradicting research results quoted earlier. It is worth stressing that in the first year of studies, copiotrophs were found most numerous in the soil subjected to reduced tillage, while in consecutive years, no-tillage turned out to be most favorable for them.

Moreover, oligotroph-to-copiotroph ratios depended on the year of study in individual experimental combinations and the value of the O:C coefficient changed from 1.4 to 4.6 (Table 3). Proportions of oligotrophs in all soil microflora were higher, both with respect to individual experimental

Table 3. The ratio between the number of oligotrophs to copiotrophs (O:C).

Year	Tillage systems	Soil layer	
		0-10 cm	10-20 cm
2010	Conventional tillage	1.4	1.4
	Reduced tillage	1.7	1.8
	No-tillage	2.8	2.2
2011	Conventional tillage	4.4	2.6
	Reduced tillage	3.9	3.2
	No-tillage	3.0	4.0
2012	Conventional tillage	2.1	1.7
	Reduced tillage	4.6	3.4
	No-tillage	2.2	2.1
Mean	Conventional tillage	2.6	2.0
	Reduced tillage	3.2	2.7
	No-tillage	2.7	2.8
	$LSD_{0.05}$	0.53	0.55

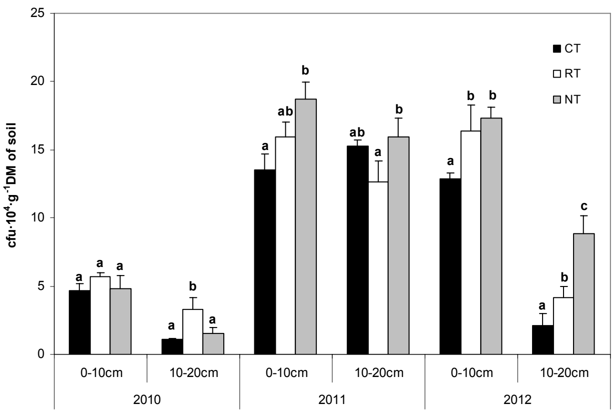

Fig. 4. Effects of tillage system on the fungi counts in the two layers of the soil profile.

years and to the mean from the entire experimental period. Differences between tillage systems turned out to be ambiguous and irregular, whereas in the case of the conventional tillage this ratio was generally the lowest. Domination of oligotrophic over copiotrophic bacteria due to economic processing of the energy substrate by oligotrophs is of significant importance from the point of view of maintenance of organic matter in the soil. According to [39], the above-mentioned domination is essential in order to maintain a constant level of soil organic matter and indicates maintenance of soil biological balance.

A distribution of fungi was found to be similar (with respect to experimental combinations) to that of copiotrophs (Fig. 4). The smallest counts of fungi were determined in conditions of conventional tillage, whereas their numbers were the highest in the case of reduced tillage (first year of studies) or in no-tillage (the remaining experimental years). This can undoubtedly be attributed to the fact that both these groups participated in the decomposition of fresh organic matter. However, fungi turned out to be characterized by strongly changing counts in consecutive years of experiments. Their numbers were distinctly lower in 2010, while in 2011 their counts were the highest. It should be emphasized that the two years differed strongly with regard to the distribution of temperatures and precipitation. June 2010, i.e. the month when soil samples were collected, was characterized by low precipitation and, consequently, the soil was dry. On the other hand, in the following year, after very dry spring months, it began to rain in June. Dry weather favored fungal sporulation, and hence led to higher numbers of fungi once the humidity became favorable [38].

Also, proportions between fungal counts in shallower and deeper soil layers in consecutive years of research were not stable. In the first and last years, quantities of fungi in the surface soil layer were several times higher, while in 2011 the differences were considerably smaller and, in the case of conventional tillage, more fungi were determined in the deeper soil layer. In the same year, copiotrophs behaved identically.

Soil fungi constitute a numerous and diverse group of organisms. Their saprophytic species contribute to a natural cycle of biogenic elements via mineralization and activation of dead organic matter. It is worth emphasizing that the observed higher content of fungi in no-tillage systems in comparison with conventional tillage did not contribute to the increase in the proportions in relation to bacteria, which would have been an unfavorable phenomenon from the point of view of soil richness and fertility [40] because bacteria also exhibited an increase of their numbers, which was even greater than that of fungi.

Enzymatic Activity of Soil

One of the indicators of soil biological condition was treated as a measure of metabolic activity of microorganisms and, simultaneously, as a factor responsible for transformations of soil constituents is soil enzymatic activity. In this research project, activities of dehydrogenases and acid phosphatase were analyzed.

The activity of dehydrogenases (Fig. 5) in both analyzed layers of the soil profile (0-10 cm and 10-20 cm) was distinctly lower in the soil tillage traditionally in comparison with the reduced tillage or no-tillage system. The stimulating influence of reduced tillage on dehydrogenase activity in the case of land cultivation under winter wheat became most apparent in 2011, in which it reached the highest values in comparison with the remaining years of experiments. In 2012, the observed differences were the least conspicuous and statistically non-significant. The activity of dehydrogenases declined together with the depth of soil profile and, in the case of the near-surface layer (0-10 cm), it was even several times higher than in deeper layers. According to Schulten et al. [41], also in this case, differences between tillage systems can be attributed to the different distribution of the organic substance in the soil profile as well as differing water-air conditions in the soil because the activity of dehydrogenases increases together with increasing quantities of organic matter and poorer soil aeration. Abundant data from the appropriate literature [18, 41] confirm that the beneficial impact of reduced soil tillage on enzyme activity is most apparent in the surface soil layer which, according to Bielińska and Mocek-Płóciniak [18], has considerable practical significance from the point of

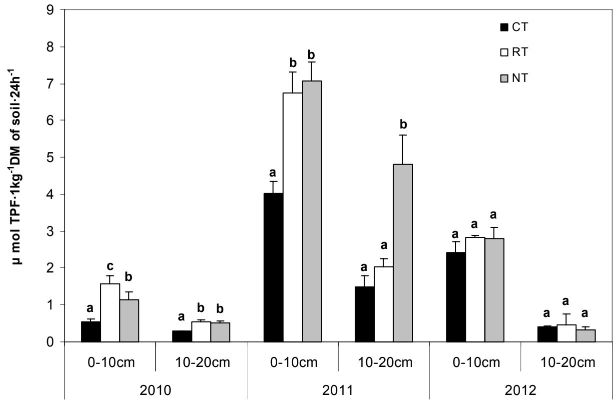

Fig. 5. Effects of tillage system on the activity of dehydrogenases in the two layers of the soil profile.

Table 4. Correlation coefficients between the different soil chemical and biological properties characteristic in the 0-10 cm soil layer.

	Organic C	Total N	C:N	pH	Total bacteria	Fungi	Oligotrophs	Copiotrophs	Dehydrogen.
Total N	0.989**								
C:N	0.726**	0.620*							
pH	-0.851**	-0.849**	-0.584						
Bacteria	0.797**	0.758**	0.712**	-0.681*					
Fungi	0.826**	0.779**	0.797**	0.603*	0.666*				
Oligotrophs	0.848**	0.810**	0.732**	-0.688*	0.910**	0.749**			
Copiotrophs	0.962**	0.942**	0.735**	-0.822**	0.754**	0.826**	0.877**		
Dehydrogen.	0.939**	0.927**	0.684*	-0.837**	0.851**	0.829**	0.916**	0.957**	
Phosphatase	0.877**	0.867**	0.642*	-0.704*	0.460	0.758**	0.606*	0.872**	0.739**

** correlation coefficient significant at significance level = 0.01
* correlation coefficient significant at significance level = 0.05

view of recognition of processes liberating nutrients stored for plants. Moreover, many researchers have reported considerable variations in the activity of soil dehydrogenases depending on the depth of soil profile. Their activity reaches maximal values in surface horizons. The activity of these enzymes declines in deeper layers of the soil profile, which is probably connected with numbers of microorganisms resulting from their spatial distribution [42, 43]. The abovementioned reports find confirmation in the research results of this study.

The activity of dehydrogenases, which can be found only inside cells of microorganisms, is considered as a general, indirect indicator of numbers and activity of microorganisms in the soil and, hence, as an indicator determining the total microbiological activity as well as fertility of the soil [44].

The performed studies revealed that the activity of acid phosphatase was nearly always significantly lower in conditions of conventional tillage. Reducent tillage (in particular no-tillage), created favorable conditions for the activity of this enzyme (Fig. 6). In the surface layer of the soil profile, this correlation was determined in all years of experiments, while in the deeper layer it was less apparent.

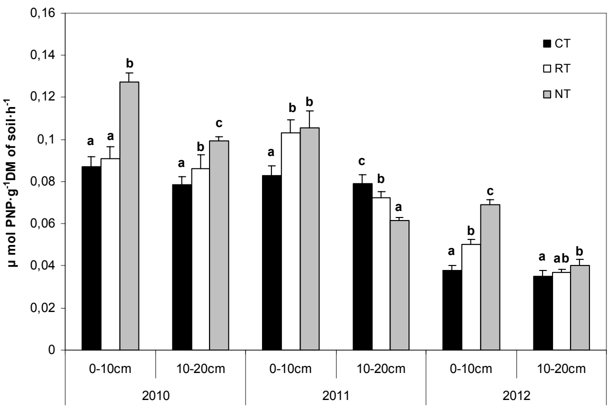

Fig. 6. Effects of tillage system on the activity of acid phosphatase in the two layers of the soil profile.

In 2011 this relationship even underwent reversal – it declined together with tillage reduced. This can be explained by the fact that, in the conditions of ploughing systems, the activity of phosphatase in the examined layers of the soil profile, in general, did not differ, whereas in no-tillage systems it was much higher in the near-surface layer than in deeper layers.

Therefore, it appears that the analyzed acid phosphatase did not derive from plants but was rather the effect of the activity of soil microorganisms and resulted from the distribution of organic matter in soil. Although many studies indicate that soil enzymatic activity is associated with biogen availability [45] and, according to Tian et al. [46], plant roots secrete acid phosphatase in conditions of shortage of available phosphorus, our results seem to corroborate the thesis that enzymatic activity is determined primarily by the level of organic matter and, consequently, it does not always reflect the content status of soil-available nutrients [47]. Nevertheless, from a practical point of view, the activity stimulation of dehydrogenases and acid phosphatase is of considerable importance in liberation processes of plant nutrients [18].

The intensity of enzymatic reactions in soil also depends on many other factors such as, for example, pH, temperature, and the presence of inhibitors. Phosphatases are enzymes that are most sensitive to changes in soil reaction. The optimal soil pH for the activity of acid phosphatase ranges from 4.0 to 6.5 [45]. Although in the described trial soil pH in individual experimental combinations was similar, nevertheless it decreased together with the declining cultivation intensity, which could have been an additional cause of higher activity of acid phosphatase in no-tillage treatments.

Quantitative and qualitative changes in soil microorganisms, soil enzyme activity, and soil chemical properties are usually closely connected with one another. In order to analyze interrelationships taking place between the determined parameters, correlation analysis between them was carried out (Table 4).

It turned out that numerous and important correlations occurred between the examined parameters. The highest positive correlation coefficients were found between all the analyzed biological parameters (numbers of soil microorganisms, activities of the examined enzymes) and the content of organic carbon and total nitrogen as well as the ratio of carbon to nitrogen. Similarly high correlations between soil enzymatic activity and the content of organic carbon were reported by, for example, Bielińska and Mocek-Płóciniak [18].

With respect to soil reaction, it was found that all the examined biological and chemical features, with the exception of numbers of fungi, were significantly negatively correlated with the pH value.

A highly significant positive correlation was determined between total bacterial counts, oligotrophic, copiotrophic bacteria and fungi, and the activity of dehydrogenases. This, according to Quemada and Menacho [48], confirms a very high participation of microorganisms in soil total biological activity, richness, and fertility. Also, other researchers [e.g. 47] have reported positive correlations between numbers of oligotrophic and copiotrophic bacteria and the activity of dehydrogenases. Similar interrelationships were also recorded between numbers of microorganisms and the activity of acid phosphatase; only with respect to total bacterial counts was this relationship not so conspicuous. A highly significant correlation demonstrated between acid phosphatase activity and numbers of fungi and copiotrophic bacteria can indicate that these microorganisms became involved in the mineralization of organic phosphorus bonds.

Among consequences of interrelationships indicated above were high correlations between the numbers of individual groups of microorganisms. The determined highly significant (r = 0.877**) positive correlation between numbers of oligotrophic and copiotrophic bacteria deserves attention.

Analyzing the relationships and correlations between microorganisms and the environment it must be remembered that crop plants, especially their root secretions (carbohydrates, amino acids, organic acids, nucleotides, and flavonic compounds), change soil physicochemical properties and, indirectly, also exert positive influence on the growth and development of soil microorganisms [49].

Conclusions

One of the basic assumptions that constitute the basis for the introduction of simplifications and restrictions in soil tllage, apart from economical aspects, is soil protection against erosion and degradation resulting from loosening, aeration and excessive drying as well as deprivation of vegetation cover – phenomena closely connected with conventional (ploughing) tillage. Among elements exerting a decisive effect on soil fertility which, at the same time, indicate directions of the phenomena taking place in the soil is soil microbial activity. In the presented study, measures of this activity in conditions of long-term application of three variants of soil tillage under winter wheat (CT, RT, and NT) comprised the size of populations of different groups of soil microorganisms, as well as soil enzymatic activity. In addition, the influence of the method of systems on such soil properties as the content of organic carbon, total nitrogen, and pH were analyzed.

Reduced tillage or resignation from tillage treatments significantly affected soil chemical parameters as well as microbiological indices of soil activity. In all years of experiments, nearly all the analyzed parameters (organic carbon, total nitrogen, total bacterial counts, numbers of oligotrophs, copiotrophs, and fungi, as well as the activity of dehydrogenases and acid phosphatase) in the near-surface layer of soil were found to be characterized by the lowest values in conditions of conventional tillage and the determined differences were statistically significant. The only exception was soil pH, which was slightly higher in the soil cultivated traditionally.

Total bacterial counts, as well as numbers of oligotrophic bacteria, assumed highest values in conditions of reduced tillage. On the other hand, numbers of copiotrophs and fungi as well as the activities of both analyzed enzymes and the content of organic carbon and nitrogen, in general, were higher in conditions of no-tillage.

In the deeper layer of the soil profile (10-20 cm), the above-mentioned relationships and trends were less regular and, in some years of investigations, they were inconsistent.

The calculated correlation coefficients revealed that the intensity of all the examined biological phenomena was distinctly linked with the concentrations of organic carbon as well as total nitrogen in soil.

It is quite evident from the obtained research results that the abandonment of conventional tillage strongly improved soil microbiological activity as expressed by numbers of soil microorganisms as well as soil enzymatic activity. From the long-term perspective, it can be said that the reduced tillage or complete resignation from tillage treatment contribute to increases in the content of organic carbon and total nitrogen in soil and, consequently, to the betterment of its richness and increase soil biological and chemical stability.

Conversion of agricultural fields from conventional practices to reduced tillage systems or no-tillage usually stimulates populations of soil fauna and microorganisms. The potential benefits of a more complex biological system within the context of a reduced agricultural system have rarely been explored. Research is needed on the interactions among the different groups of organisms at the community level. The impacts of soil macrofauna on multiple functions in the soil, including soil physical properties, organic matter stabilization, and nutrient cycling, require further investigation in linkage with work on smaller soil organisms.

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