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ORIGINAL PAPER

CHEMICAL PROPERTIES OF SOIL AND OCCURRENCE OF EARTHWORMS IN SOIL IN RESPONSE TO SOIL COMPACTION AND DIFFERENT SOIL TILLAGE IN CEREALS*

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Abstract

This article discusses the results of our experiment obtained in the years 2009-2012. The aim of this experiment has been to assess changes in the chemical composition of soil, as well as in the number and biomass of Lumbricidae under winter wheat and spring barley fields, as influenced by soil compaction and different tillage methods. There was less organic carbon and P in soil under winter wheat (compacted soil and without soil compaction) if tilled with a subsoiler (cultivation treatment U-2) than with a plough. In soil under spring barley (compacted soil), the lowest pH was observed after plough tillage, and a reverse situation was noted in tillage treatment U-2 (with a subsoiler). Most P and K in soil from the plots with compacted or uncompacted soil were determined in the U-4 soil cultivation treatment, and the content of these elements was higher than in the plough tillage treatments. Before wheat was harvested (compacted soil), the number of earthworms was nearly three-fold higher in tillage treatment U-3, whereas among plots without compaction higher biomass of earthworms was identified in soil submitted to U-2 and U-4 tillage treatments. After the emergence of spring barley (compacted soil), significantly more earthworms, relative to the plough tillage (control), were determined in the U-2 treatment. In soil under winter wheat and with plough tillage (plots without soil compaction), an increase in soil pH was negatively correlated with the number of earthworms. Under winter wheat, an increase in the content of nitrogen and magnesium in soil subsequent to soil tillage treatment U-4 (plots without compaction) positively correlated with the density of earthworms per area unit, while a rise in the soil content of P considerably lowered the number of earthworms on plots with compacted soil. A similar situation was observed under spring barley after the ploughing treatment on plots without soil compaction.

Keywords: quality of soil, number and biomass of earthworm, winter wheat, spring barley.

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INTRODUCTION

Soil tillage is one of the primary components of agrotechnology, having a strong impact on conditions and outcome of crop production (MAŁECKA, BLECHARCZYK 2008). The main goal of soil tillage is to create optimal conditions for the growth and development of crops (JASKULSKI et al. 2012); another purpose is to counteract negative effects of contemporary technologies arising from technological progress – mainly soil compaction (BULIŃSKI, MARCZUK 2007). Plough tillage with additional soil improvement treatments as well as the repeated transit of heavy machines and implements over fields typically intensify soil packing. Consequently, physical and chemical properties of soil change and its natural state of biological equilibrium is distorted (AIKINS, AFUAKWA 2012, ABDOLLAHI, MUNKHOLM 2014). Such negative changes lead to gradual degradation of soil and declining yields of cultivated crops (MAŁECKA et al. 2012).

The damage due to compacted soil can be so severe that conventional plough tillage methods are increasingly often abandoned to the advantage of proecological soil cultivation solutions, where the intensity and depth of soil treatments are diminished to the extent where direct sowing is implemented, which is an extremely reduced form of soil cultivation (BISKUPSKI et al. 2009). Research results indicate that simplifications in soil cultivation can impede the soil compaction process, in addition to which they can differentiate soil chemical properties and change the conditions for the development of useful fauna in the cultivated soil horizon (CURRY et al. 2002, BLECHARCZYK et al. 2007, ABDOLLAHI, MUNKHOLM 2014, CRITTENDEN et al. 2014). Beside soil tillage techniques, another important factor is the selection of crops in a crop rotation sequence, for example sowing crops that are similar in their biological traits and agrotechnical requirements, e.g. a succession of winter wheat and spring barley, can result in a change in the soil's chemical properties and distrupt its biological balance (MAŁECKA et al. 2012, KUNTZ et al. 2013).

The objective of this study has been to determine the effect of soil compaction and different soil tillage technologies on the chemical characteristics of soil as well as on the abundance and biomass of Lumbricidae in soil cropped with winter wheat and spring barley.

MATERIAL AND METHODS

The research was based on results obtained from a controlled, long-term, two-factorial field experiment, conducted at the Production and Experimental Company in Bałcyny (53°36′ N, 19°51′ E), which provides experimental facilities for the University of Warmia and Mazury in Olsztyn. The experiment was laid out in a pattern of randomly selected blocks with 4 replications. The number of plots was 32, and the surface area of each plot was 30 m^2.

The experiment was established on the soil classified as a Haplic Luvisol (Aric, Ochric) formed from loamy sand (LS) on sandy loam (SL) – IUSS Working Group WRB (2015). The topmost horizon (0-20 cm) contained from 10 to 10.7 g kg^{-1} C org, had acidic to slightly acidic pH (pH_{KCl} 5.4-5.6), and the following content of elements: phosphorus from 74.0 to 82.1 mg kg (moderate abundance), potassium from 98.2 to 160.1 mg kg (low to moderate abundance) and magnesium from 36.1 to 39.0 mg kg (low richness).

Four soil tillage technologies were compared in a three-field rotation system: winter oilseed rape (variety Mendel), winter wheat (var. Ludwig) and spring barley (var. Justina). The data for the research were obtained from the plots sown with wheat and barley.

Factors of the experiment**:**

A – degree of soil compaction before crop sowing;

- control treatment, without soil compaction;
- treatment with soil compaction after the crop preceeding the main crop was harvested. Passage of a tractor and trailer weighing *ca* 6 t, and moving trace by trace:

B – four different ways to prepare a field for sowing the test plant.

The sequence and choice of soil tillage treatments are given in Table 1.

Sowing the crops on all plots was performed with a combine sowing machine and cultivator manufactured by Väderstad. Winter wheat was sown on 17 September 2009, in an amount of 205 kg·ha^{-1}, and spring barley was seeded on 30 March 2011, in a dose of 170 kg ha^{-1}. The plots received only mineral fertiliation, with the following doses of pure element (kg ha^{-1}): winter

Table 1

Choice and sequence of soil tillage treatments before sowing winter wheat and spring barley

Tillage	U-1*	U-2	U-3	U-4
Winter wheat				
After harvest	skimming10 cm + + harrowing	rotary cultivator	diskcultivator + + harrowing + + cultivating	chisel (40 cm)
Before harvest	sowing ploughing 20 cm	sowing ploughing 25 cm	sowing ploughing 20 cm	single ploughing 30 cm
Spring barley				
After harvest	skimming10 cm + + harrowing	skimming 10 cm + + harrowing + + cultivating	cultivator	–
Pre-winter	winter ploughing 30 cm	winter ploughing 25 cm	winter ploughing 25-30 cm	single ploughing 30 cm

***** U-1 – conventional tillage (control object) wheat N – 50, P – 35 and K – 100, spring barley N – 80, P – 30 and K – 83. Plant protection chemicals were applied depending on the severity of infestation with agrophages. The cereals were harvested at full maturity of grain (BBCH 89-92).

Soil for chemical analyses was sampled in the spring of 2008 (before the experiment was started), and the sampling was repeated before the harvest of both cereals (BBCH 89-92). Samples for analyses were collected from the topmost soil horizon, 0-20 cm deep, at 2 fixed sites from each plot. The following determinations were made: pH (1 mol KCL), content of C org, total N and available forms of phorphorus, potassium and magnesium. The soil pH was determined by potentiometry, organic carbon – by spectrophotometric method, total nitrogen – by titration, potassium – by flame photometry, and magnesium – by flame atomic absorbtion spectrometry. All analyses were made in a certified laboratory at the Chemical Agricultural Station in Olsztyn.

Earthworms were captured from soil using a 0.4% solution of formalin. The solution was poured onto the plots after the plant residue had been removed. Next, earthworms were cleansed in a water bath and anaesthetised in 30% ethanol. Having been dried in 75% ethanol, the earthworms were preserved in 4% formalin solution, after which they were counted and weighed. Soil samples were collected on two dates (after plant emergence and before harvest) form an area of 0.25 m^2, at a fixed site on each plot. All harvest data were converted per surface area of $1m^2$.

The results underwent statistical processing. The Shapiro-Wilk normality test at $p<0.05$ was applied first. It showed that the number and mass of earthworms did not satisfy the criteria of normal distribution. Thus, for an evaluation of the significance of differences between the particular reduced tillage treatments and conventional (control) soil tillage, and between the treatments with and without soil compaction, the non-parametric *U* Mann-Whitney test was applied, at a significance level of $\alpha = 0.05$. The *t*-Sudent test at $p<0.05$ was carried out to evaluate the significance of differences between the chemical properties of soil under the winter wheat and spring barley. The assessment of the correlations between the number and mass of earthworms versus the chemical properties of soil was based on the Spearman's rank correlation coefficients. All calculations were supported by the software Statistica® 13 (TIBCO Software Inc. 2017).

The weather conditions during the experiment were variable (Table 2). During the vernal growth and development of winter wheat the average air temp. (13.0°C) as well as the total rainfall (395.5 mm) surpassed the multi-annual means. March and April of 2010 were quite warm (2.1 and 7.9°C) and dry (23.8 and 9.4 mm precipitation). In May, the crops compensated for the temporary shortage of moisture, as the total precipitation in that month (105.5 mm) was by 48 mm higher than the average long-term precipitation. Likewise, in June, July and August, there were more rainfalls

Table 2

Temperatures and atmospheric precipitation during the growing season of winter wheat and spring barley

Years	Months									Total/ mean July-Oct	Total/ mean March-July
	Aug	Sept	Oct	Mar	Apr	May	June	July	Aug		
Mean air temperature (°C)											
2009/2010	18.1	14.6	8.6	3.5	8.4	13.9	15.2	19.0	17.9	13.8	13.0
2010/2011	18.5	14.7	5.9	2.1	7.9	12.0	15.7	20.8	19.3	13.0	13.0
2012	x	x	x	2.0	9.7	13.6	17.5	18.0	18.1	x	13.2
1962-2002	16.8	12.6	8.1	1.4	7.0	12.5	15.8	17.2	16.8	12.5	11.8
Precipitation (mm)											
2009/2010	83.6	38.9	29.9	21.3	44.7	42.5	107.2	112.2	75.2	152.4	403.1
2010/2011	25.7	15.6	58.5	23.8	9.4	105.5	73.7	87.8	99.3	99.8	399.5
2012	x	x	x	8.6	33.7	41.5	56.2	171.9	83.6	x	395.9
1962-2002	75.2	59.1	54.0	28.8	35.4	57.6	69.5	81.6	25.7	188.3	298.6

than the long-term mean amounts recorded in the vicinity of the village Bałcyny, but the thermal conditions created quite suitable conditions for the growth and development of the analysed cereal. Warm June (15.7°C) and very warm July (especially from 10^{th} to 30^{th} of that month), with an average temperature nearly 21% higher than the multi-year average caused the cereal to reach full ripeness at the end of July.

In 2011, the growth and development of spring barley generally proceeded under unfavourable conditions (Table 2). There was drought persisting from March to the end of June, and the lowest rainfall relative to the multi-annual average occurred in May (41.5 mm) and in June (56.2 mm), that is during the ear formation and grain filling stages. Moreover, the air temperature in both months was higher by 1.1 and 1.7°C than in the multi-year period, which aggravated the water shortage. July of 2011 proved to be extremely wet, with the sum of rainfall more than double the long-term mean precipitation.

RESULTS

The experimental factors differentiated the soil reaction and richness in available macronutrients. Under winter wheat and spring triticale, on compacted plots versus uncompacted ones, significantly lower soil pH (pH 5.83) was found in the ploughing treatment (control) – Table 3. In addition, significantly lower soil pH was determined under spring barley (plots compacted soil) in the cultivation treatments U-3 and U-4.

Table 3

Chemical properties of soil before winter wheat and spring barley harvest

Chemical properties	Tillage methods*	Winter wheat		p	Spring barlely		p
		degre of soil compaction			degre of soil compaction		
		A $\bar{x}$	B $\bar{x}$		A $\bar{x}$	B $\bar{x}$	
pH	U-1	6.11	5.83	<0.001	6.24	5.92	0.003
	U-2	5.97	5.80	0.194	6.24	6.05	0.068
	U-3	5.95	5.69	0.067	6.14	5.93	0.035
	U-4	5.85	5.88	0.745	6.24	5.97	0.019
C org (g kg^{-1})	U-1	12.23	10.15	0.006	10.30	10.10	0.292
	U-2	11.58	9.03	0.016	10.10	10.20	0.488
	U-3	11.28	9.98	0.004	10.00	10.30	0.272
	U-4	12.95	10.00	<0.001	10.10	10.20	0.708
Total N (g kg^{-1})	U-1	0.90	0.97	0.127	0.89	0.91	0.653
	U-2	0.86	0.98	0.047	0.87	0.91	0.196
	U-3	0.94	1.50	0.129	0.86	0.89	0.617
	U-4	1.02	1.19	0.358	0.88	0.94	0.520
C:N	U-1	13.62	10.44	0.002	11.61	11.10	0.340
	U-2	13.56	9.24	<0.001	11.67	11.22	0.169
	U-3	12.12	7.33	0.021	11.69	11.62	0.926
	U-4	13.03	8.72	0.045	11.67	10.92	0.399
P (mg kg^{-1})	U-1	94.23	72.43	0.005	106.40	82.40	<0.001
	U-2	82.00	75.85	0.002	98.50	98.50	0.999
	U-3	88.48	70.58	<0.001	100.30	99.40	0.183
	U-4	87.15	77.55	<0.001	109.90	112.90	0.718
K mg kg^{-1}	U-1	111.18	114.48	0.734	127.80	156.00	<0.001
	U-2	109.55	98.80	<0.001	122.80	166.00	0.001
	U-3	103.83	96.33	0.003	114.50	205.75	0.001
	U-4	106.18	97.08	0.033	149.40	206.70	<0.001
Mg (mg kg^{-1})	U-1	44.03	39.23	0.053	45.20	45.20	0.999
	U-2	43.40	41.60	0.046	45.80	45.83	0.962
	U-3	45.75	41.00	<0.001	43.40	44.60	0.544
	U-4	44.55	40.38	0.007	46.35	46.40	0.939

* Explanation see Table 1. A – without compaction, B – compacted soil, $\bar{x}$ – mean, p – *t*-Student test probability, significant with $p < 0.05$

Under winter wheat (plots without soil compaction) the tested soil cultivation technologies significantly raised the pool of organic C in soil in comparison with compacted plots. The largest difference in the content of this nutrient in soil (2.95 g kg^{-1}) was determined after single ploughing (cultivation treatment U-4). No significant differences in the soil content of N were found under winter wheat and spring barley (compacted soil and without soil compaction). An exception was the treatment U-2 under winter wheat, although the difference between treatments with compacted soil and without soil compaction was on the borderline of statistical significance (p = 0.047). Under winter wheat (plots without compaction), the tested cultivation treatments significantly increased the C:N ratio and considerably raised the soil richness in available P in comparison with the analogous cultivation treatments on compacted plots. A highly significant difference in the soil content of this element was noted after cultivation treatments U-3 and U-4. In turn, significantly less P (by 24 m kg^{-1}) was determined after cultivation treatment U-1 (control) on plots with compacted soil. Under winter wheat on plots without compaction, relative to compacted ones, a signifucantly higher content of potassium was observed after treatments U-2, U-3 and U-4. Under spring barley, the tested soil cultivation technologies (plots with compaction relative to uncompacted plots) significantly increased the content of available K in soil. The biggest differences in the soil content of potassium were determined after treatment U-3 (soil cultivator, pre-winter ploughing to 25-30 cm depth) and after treatment U-4 (single ploughing). Under winter wheat (plots without soil compaction), relative to plots with compacted soil, significantly more Mg in soil was noted after reduced soil tillage treatments U-2, U-3 and U-4. The greatest difference in the soil content of this element was observed after treatment U-3 (disc harrow, cultivator, harrow and pre-sowing ploughing to 20 cm depth).

The experimental factors had a significant impact on the number and mass of earthworms in the topsoil (0-20 cm) – Table 4. The number of earthworms in the 0-20 cm soil layer per surface area unit was nearly three-fold higher in soil under plots with compacted soil and submitted to tillage treatment U-3 (disc harrow, cultivator and harrow + pre-sowing ploughing to 25 cm depth) Where soil was compacted, the mass of earthworms was significantly lower in soil under tillage treatment U-2 (rotovator + pre-sowing ploughing to 25 cm depth) than in soil submitted to the analogous soil tillage but without compaction. The use of a subsoiler in post-harvest tillage followed by a single ploughing treatment to a depth of 30 cm (tillage treatment U-4) on compacted soil resulted in a neraly 1.5-fold increase in the biomass of earthworms compared with plots without soil compaction.

Before the harvest of winter wheat, tillage treatments U-2 and U-3 significantly increased the biomass of earthworms in soil under plots without soil compaction relative to the analogous treatments under plots with compaction. Soil tillage treatment U-3 led to a five-fold rise in the mass of earthworms under plots with compacted soil (Table 4).

Tabele 4

Number and mass of earthworms in the tested soil tillage treatments, with or without soil compaction, after emergence and before harvest of winter wheat and spring barley

Tillage system*	Degree of soil compaction		p	Degree of soil compaction		p
	A	B		A	B	
	number after emergence			mass after emergence		
	$\bar{x} \pm s$	$\bar{x} \pm s$		$\bar{x} \pm s$	$\bar{x} \pm s$	
	Winter wheat					
U-1	5.25±2.75	4.00±2.16	0.5019	6.30±0.15	5.99±1.47	0.6923
U-2	3.75±2.63	2.75±1.50	0.5334	6.41±0.18	5.03±0.51	0.0022
U-3	3.50±1.29	5.75±1.50	0.0633	9.13±3.33	12.09±0.66	0.1123
U-4	6.50±3.11	8.50±4.04	0.4626	8.13±1.26	12.35±1.46	0.0047
	number before harvest			mass before harvest		
U-1	2.25±1.89	3.00±2.58	0.6559	4.25±2.53	6.80±1.33	0.1243
U-2	3.00±1.83	2.50±1.29	0.6704	4.33±1.79	1.89±0.36	0.0368
U-3	2.00±1.41	5.50±1.00	0.0068	1.76±0.24	8.81±0.36	<0.0001
U-4	6.00±2.58	5.25±2.22	0.6748	8.23±0.59	4.78±1.42	0.0041
	Spring barley					
	number after emergence			mass after emergence		
U-1	3.25±2.06	1.75±0.96	0.2350	3.71±0.36	1.43±0.48	0.0003
U-2	0.75±0.50	3.50±0.58	0.0004	1.19±0.16	5.49±0.47	<0.0001
U-3	2.50±1.73	3.75±2.75	0.4714	1.68±0.66	2.21±0.63	0.2924
U-4	0.75±0.50	2.50±2.52	0.2215	1.04±0.18	1.69±0.66	0.1029
	number before harvest			mass before harvest		
U-1	5.50±5.74	4.50±3.00	0.7681	11.63±1.61	13.48±3.64	0.3881
U-2	6.00±5.10	6.75±2.87	0.8063	19.84±0.77	14.69±2.16	0.0041
U-3	8.25±6.85	8.00±1.15	0.9450	28.83±1.82	13.87±0.73	<0.0001
U-4	7.50±2.08	7.00±3.46	0.8128	19.77±1.74	15.17±1.99	0.0131

* Explanation – see Table 1. A – without soil compaction, B – with soil compaction, $\bar{x} \pm$ s mean ± standard deviation, p – U - Mann-Whitney's test probability

On the plots without soil compaction, after plant emergence and before harvest, a larger biomass of Lumbricidae was observed in treatment U-4 than in the ploughed soil (control). In turn, under compacted soil, soil tillage treatments U-3 and U-4 caused a considerable increase in the biomass of earthworms after plant emergence, while U-2 resulted in the biomass increase noticed before harvest (Table 5).

After the emergence of spring barley, over 37% greater density of earthworms was noted on compacted soil (Table 5). The soil tillage treatment U-2 raised the number and biomass of Lumbricidae by over 4.5-fold compared

Table 5

Comparison of the number and mass of earthworms in reduced tillage systems after emergence and before harvest of winter wheat and spring barley

Tillage system[x]	Degree of soil compaction			
	A	B	A	B
	winter wheat – after emergence			
	number		mass	
U-1	x	x	x	x
U-2	ns	ns	ns	ns
U-3	ns	ns	ns	**
U-4	ns	ns	*	**
Winter wheat – before harvest				
U-1	x	x	x	x
U-2	ns	ns	ns	*
U-3	ns	ns	ns	*
U-4	ns	ns	*	ns
Spring barley – after emergence				
U-1	x	x	x	x
U-2	ns	*	**	**
U-3	ns	ns	**	ns
U-4	ns	ns	**	ns
Srping barley – before harvest				
U-1	x	x	x	x
U-2	ns	ns	**	ns
U-3	ns	ns	**	ns
U-4	ns	ns	**	ns

[x] Explanation – see Table 1. A – without soil compaction, B – with soil compaction, ns – non-significant value, * significance at $p < 0.05$, ** significance at $p < 0.01$

to the analogous soil tillage on non-compacted plots, and significantly increased the density of specimens per surface area unit relative to the ploughed treatment (the control treatment) (Table 5). Similarly, a significantly greater biomass of earthworms was found after U-1 tillage treatment performed on plots without soil compaction. The plots without soil compaction were found to present a highly significant increase in the value of the above parameter after the tillage treatments U-2, U-3 and U-4, relative to the ploughed soil treatment (the control treatment), whereas the same situation among the compacted plots occurred only after the implementation of U-2 tillage technology.

On the second assessment date (before barley harvest), the soil tillage treatment U-3 doubled the biomass of earthworms in soil under plots without compaction. A similar increase in this parameter was observed after the implementation of soil tillage treatments U-2 and U-4. On that date, a considerable rise in the biomass of Lumbricidae, compared to the ploughed soil (control), was observed on plots with compacted soil where U-2, U-3 or U-4 soil tillage technologies had been implemented.

Our analysis of the correlations between the soil richness with nutrients and the abundance of Lumbricidae in soil under winter wheat showed that the soil pH in ploughed soil (control) was negatively correlated with the number of earthworms in plots without soil compaction (Table 6).

After the soil had been cultivated with a subsoiler and a plough (single ploughing), as the nitrogen and magnesium content of soil increased, so did the density of earthworms per surface area unit (a significant rise), whereas an increase in the soil content of phosphorus correlated negatively with the number of specimens on compacted soil. In turn, following soil tillage

Table 6

Spearman's rank correlation coefficients between the number and biomass of earthworms and the chemical properties of soil cropped with winter wheat

Tillage system	pH	C org.	Total N	P	K	Mg
Number of earthworms before winter wheat harvest – plots without soil compaction						
U-1	-0.99*	-0.15	-0.30	0.76	0.47	0.17
U-2	-0.59	-0.78	-0.14	-0.09	-0.35	-0.05
U-3	0.71	-0.43	0.38	0.41	0.37	-0.34
U-4	-0.15	-0.56	0.96*	0.31	0.89	0.98*
Number of earthworms before winter wheat harvest – compacted soil						
U-1	-0.38	0.35	-0.95	0.88	0.00	-0.49
U-2	0.57	0.60	-0.67	-0.57	0.03	-0.29
U-3	0.00	0.06	-0.64	-0.45	0.71	0.08
U-4	-0.81	-0.41	-0.11	-0.96*	0.93	0.57
Mass of earthworms before winter wheat harvest – plots without soil compaction						
U-1	0.49	0.72	-0.15	-0.57	-0.60	-0.83
U-2	0.97*	0.22	-0.45	0.46	-0.33	-0.12
U-3	0.19	-0.39	0.28	-0.05	0.21	-0.69
U-4	0.14	0.90	-0.37	-0.92	-0.27	-0.66
Mass of earthworms before winter wheat harvest – compacted soil						
U-1	0.96*	-0.18	0.74	-0.88	-0.01	0.12
U-2	-0.83	-0.62	0.66	0.30	0.43	-0.24
U-3	0.74	0.77	-0.32	-0.24	0.24	0.74
U-4	0.81	0.34	0.14	0.93	-0.89	-0.54

* significant at $p < 0.05$, ** significant at $p < 0.01$

treatment U-2 (plots without compaction), a rise in the soil pH significantly increased the biomass of Lumbricidae; a similar effect was achieved on compacted plots after the ploughing treatment (control).

With respect to spring barley, a rise in the soil content of phosphorus after soil ploughing (plots without compaction) significantly negatively correlated with the number of earthworms. After soil tillage treatment U-2, an increase in the soil content of magnesium was followed by a significant increase in the number of earthworms per area unit (Table 7).

Table 7

Spearman's rank correlation coefficients between the number and biomass of earthworms and the chemical properties of soil cropped with spring barley

Tillage system	pH	C org.	Total N	P	K	Mg
Number of earthworms before spring barley harvest – plots without soil compaction						
U-1	0.86	-0.08	0.14	-0.97*	0.37	-0.21
U-2	0.64	-0.79	-0.24	-0.79	-0.79	0.97*
U-3	0.67	-0.60	-0.49	-0.11	-0.35	-0.35
U-4	0.52	0.72	0.11	0.18	0.87	0.12
Number of earthworms before spring barley harvest – compacted soil						
U-1	0.79	0.12	0.79	-0.05	-0.75	0.82
U-2	0.34	0.00	0.32	-0.60	0.33	0.59
U-3	-0.67	0.12	-0.77	-0.06	0.38	0.20
U-4	-0.25	-0.27	0.04	-0.66	0.00	0.63
Mass of earthworms before spring barley harvest – plots without soil compaction						
U-1	0.28	0.23	0.28	0.25	-0.15	-0.90
U-2	0.23	0.37	-0.20	-0.11	0.14	-0.69
U-3	0.75	0.32	0.67	0.71	0.86	-0.76
U-4	0.10	0.60	0.03	-0.27	0.69	-0.28
Mass of earthworms before spring barley harvest – compacted soil						
U-1	0.30	0.06	0.30	-0.31	-0.74	0.68
U-2	0.04	0.60	0.14	0.28	0.17	-0.68
U-3	-0.09	0.70	-0.21	-0.53	0.24	-0.05
U-4	0.36	0.31	0.14	0.79	0.01	-0.68

* significant at $p < 0.05$, ** significant at $p < 0.01$

DISCUSSION

Reduced soil tillage technologies lead to an uneven distribution of nutrients in the soil profile, which in turn changes the chemical properties of soil (Thomas et al. 2007, Wright et al. 2007). In this study, the lowest pH of soil under winter wheat (plots without compaction) was noted in the U-4 soil tillage treatment (a subsoiler to 40 cm depth + single ploughing to 30 cm), whereas among compacted plots, the lowest soil pH corresponded to treatment U-3. Under spring barley, the lowest soil pH occurred after the ploughing tillage treatment (control), in contrast to U-2. Similar results were reported by Małecka et al. (2012), who determined lower soil reaction after reduced tillage than after conventional soil cultivation. In another study by Małecka et al. (2007), the researchers documented the fact that the soil pH remained stable after conventional tillage, while the use of a stubble cultivator slightly decreased the pH of soil (by 0.2-0.3 unit). In our experiment, soil under winter wheat (compacted soil and without soil compaction) treated according to the U-2 tillage technology contained less organic carbon, while after U-3 it had less K than ploughed soil (control treatment).

Concerning the plots sown with spring barley, the least of available P and K was noted in soil after the U-2 and U-3 tillage systems (plots without soil compaction), although on compacted soil the control ploughing system produced a similar result. Cudzik et al. (2011) noted a larger content of organic carbon in a reduced tillage system compared with the traditional one. Blecharczyk et al. (2007) documented the fact that the use of a disc harrow in soil tillage, compared to conventional ploughing, raised the content of organic carbon, total nitrogen, and available forms of P and Mg in the soil horizon down to 5 cm, although the content of these macroelements in a deeper soil horizon (10-20 cm) decreased. These results correspond, to some extent, with the ones obtained by López-Fando and Parado (2009), Limousin and Tessier (2007), Martin-Rueda et al. (2007) and Thomas et al. (2007). The cited authors indicate that the higher content of organic carbon and total nitrogen in soil after simplified soil cultivation is caused by slower mineralisation of organic matter in soil.

On the other hand, Małecka et al. (2012), having completed a 11-year--long series of experiments, concluded that more organic C and total N were in soil subjected to reduced tillage, and the difference relative to conventional soil cultivation was 30.4% for organic C and over 21% for total N. Similar results were obtained by López-Fando and Parado (2009), Shi et al. (2012) and Thomas et al. (2007). As for macronutrients, Martin Rueda et al. (2007) demonstrated higher concentrations of P, K and Mg in soil under a reduced tillage system than cultivated traditionally by ploughing. Likewise, Małecka et al. (2007) noted that the content of macronutrients, especially P, was higher (by about 50% for the element mentioned) when soil tillage was reduced rather than consisting of traditional ploughing.

Soil tillage has an extremely unfavourable influence on the species composition, number and activity of soil organisms (Urmler 2010). Chatterjee and Lal (2009) maintain that the range of changes induced in soil by tillage depends on the amount and distribution of rainfall, temperatures, type of soil, crop rotation, fertilisation, etc. Lenart, Sławiński (2010) found a lower number and biomass of earthworms after a ploughing system, and the values of these attributes were much higher in autumn than in spring. In our research, the number of Lumbricidae was nearly three-fold lower before winter wheat harvest after the U-3 tillage treatment (plots without compaction). On the other hand, the use of a rotovator (compacted soil) decreased the biomass of earthworms after plant emergence, and the biomass of earthworms was nearly 1.5-fold higher in soil treated with a subsoiler (compacted soil) than in the plots submitted to the analogous soil cultivation treatment but without soil compaction. On both dates of analysis (plots without compaction), a much greater biomass of earthworms, relative to the control ploughing treatment, was observed in soil subjected to the U-4 tillage system; the same situation was found on compacted soil subjected to the U-2 and U-3 tillage systems after plant emergence and to U-2 and U-3 before harvest. Curry et al. (2002) claim that any drastic technologies of soil cultivation can eliminate whole populations of earthworms in just one plant growing season, and Westernacher-Dotzler (1992) report that as many as 50% of specimens die directly due to a soil tillage treatment while an additional 39% die because of the excessive dryness of soil.

The biomass and number of earthworms are significantly affected by the choice of crops in a crop rotation system. Schmidt and Curry (2001) state that the cultivation of deeply rooted species or catch crops makes it easier for earthworms to colonise soil. These authors have documented approximately 5-fold more earthworms in soil under organically grown winter wheat than under its multi-year monoculture. Felten and Emmerling (2011) proved that the number and biomass of Lumbricidae were not significantly differentiated under fields cropped with cereals, oilseed rape and maize, and the density of earthworms varied from 3.0 (± 1.4) per 1 m^2 under maize to 4.0 (± 0.9) under oilseed rape and 3.7(± 1.1) individuals per 1 m^2 under cereals.

In this experiment, soil tillage U-2 (skimming, harrowing, pre-sowing ploughing) increased the number and biomass of earthworms in soil under spring barley following the plant emergence by over 4.5-fold relative to plots not compacted, and significantly increased the values of both parameters compared to the control, ploughed soil. Before the harvest of the crops, a considerable increase in the biomass of earthworms was noted on compacted soil following the cultivation systems U-2, U-3 and U-4. Szulc and Dubas (2007) demonstrated that under reduced soil tillage, the density of Lumbricidae was strongly differentiated by the soil moisture content, and was invariably larger than after the soil tillage with ploughing. Kuntz et al. (2013) claim that reduced soil tillage raised by 67% the number of earthworms and by 48% their biomass in comparison to their number and mass in ploughed soil. Similar results were also reported by Metzke et al. (2007). An experiment conducted by Crittenden et al. (2014) showed that the ploughing tillage and reduced tilage systems in organic farming can demonstrably decrease the density of Lumbricidae in a period of 21 days after a ploughing treatment in autumn, but in spring of the following year the population of earthworms regained its original size and no distinct differences were observed between the ploughing and reduced soil cultivation systems. Crittenden et al. (2014) state that this is most probably a consequence of organic matter becoming more easily accessible in ploughed soil than under a reduced tillage system.

The investigations completed thus far have failed to resolve the question how soil tillage simplifications affect the living environment of soil organisms (Metzke et al. 2007, Szulc, Dubas 2007, Felten, Emmerling 2011, Crittenden et al. 2014). Schmidt and Curry (2001) state that the species composition, biomass and abundance of earthworms are significantly influenced by the choice of crops for a crop rotation system and the changeability of environmental conditions. One of the major problems that Polish agriculture is currently facing is the regional, and sometimes even local variability of the environment. In the nearest future, therefore, it is recommended to continue studies on Lumbricidae, and to gradually limit the use of intensive ploughing soil cultivation for the benefit of reduced soil tillage technologies. It is important to take into account, while selecting solutions to be implemented, the regional and local habitat conditions, knowledge of the requirements that the crops to be grown have, and the technical equipment that a given farm possesses.

CONCLUSIONS

1. The experimental factors differentiated the soil pH and its content of available macronutrients. The ploughing soil tillage technology under winter wheat and spring barley (plots with soil compaction) decreased the soil pH to a greatest degree. Under winter wheat (plots with compaction), the tested soil tillage technologies raised the content of carbon and phosphorus in soil in comparison to the analogous cultivation treatments on compacted plots, Most carbon was determined after single ploughing (treatment U-4).

2. Less phosphorus was determined under spring barley after ploughing tillage (plots with compaction), whereas more K and Mg in soil under winter wheat (plots without compaction) was recorded after the reduced tillage treatments U-2, U-3 and U-4. Under spring barley on plots with soil compaction, in comparison with uncompacted ones, the tested soil tillage treatments considerably increased the content of available K.

3. The soil tillage treatment U-3 on plots without compaction decreased the number of Lumbricidae before the harvest of winter wheat. In turn, the use of a rotary cultivator and perfoming the pre-sowing ploughing treatment to the depth of 20 cm decreased the biomass of earthworms after

plant emergence, whereas the use of a subsoiler (soil tillage treatment U-4) resulted in the opposite effect.

4. The reduced tillage treatment U-2 led to the highest rise in the number and biomass of earthworms after emergence of spring barley on compacted plots, while the highest increase in the biomass of Lumbricidae before harvest, in comparison with the ploughing technology (the control treatment), was noted after the reduced soil tillage treatments U-2, U-3 and U-4 (plots without compaction).

5. After the soil tillage system U-4, as the soil content of N and Mg increased, so did the density of earthworms; contrary to this, an increase in the soil content of P correlated negatively with the number of earthworms in soil under compacted plots. In soil under plots cropped with spring barley, a rise in the phosphorus content achieved after the ploughing soil tillage (plots without soil compaction) correlated significantly negatively with the number of earthworms.

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