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ORIGINAL PAPER

EFFECT OF SOIL COMPACTION AND DIFFERENT SOIL TILLAGE SYSTEMS ON CHEMICAL PROPERTIES OF SOIL AND PRESENCE OF EARTHWORMS IN WINTER OILSEED RAPE FIELDS*

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Abstract

The research objective has been to assess the impact of soil compaction and reduced tillage on changes in the chemical properties of soil, and on the number and biomass of earthworms in soil cropped with two varieties of winter oilseed rape. The experimental factors were: soil compaction before sowing the crops (with and without soil compaction) and 4 tillage systems (U-1 ploughing tillage – the control; U-2 subsoiler, disc harrow, cultivator, harrow and pre-sowing ploughing to a depth of 20 cm; U-3 shallow ploughing; U-4 single ploughing). The highest soil pH in fields cropped with the winter oilseed rape cultivars Californium and Mendel was recorded after a single ploughing treatment without soil compaction. The U-2 tillage system decreased the soil content of organic carbon on plots with compaction. The tested tillage systems significantly increased the content of K in both varieties of winter oilseed rape grown on plots with soil compaction. Once oilseed rape plants (cv. Californium) emerged, a single ploughing treatment (plots without compaction) raised by 73% the number of earthworms in soil and more than doubled their mass relative to the analogous treatments on plots with soil compaction. Before oilseed rape harvest, after a single ploughing treatment (plots with compaction) the number of earthworms more than doubled and its biomass increased by nearly 2.5-fold relative to the analogous treatments on plots without soil compaction. After emergence of winter oilseed rape (cv. Mendel), the U-3 tillage method before the harvest (plots with compaction) – compared to the analogous treatment on plots without compaction – raised the number of earthworms by over two-fold, and the U-2 tillage before the harvest (plots with compaction) significantly reduced the biomass of earthworms relative to the complete ploughing system (control).

Keywords: soil compaction, soil tillage, soil organic matter, soil pH, available P, K and Mg, number and biomass of earthworm, winter oilseed rape.

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INTRODUCTION

Progressing mechanisation in agriculture and intensification all types of field work cause significant changes in the way fields are prepared for sowing crops. The research results indicate that the major disadvantage of soil ploughing, apart from high enery- and labour-consumption, is the increased compaction of the topsoil (and subsoil) due to the repeated movement of heavy agricultural machines with implements and other vehicles (Buliński, Marczuk 2007, Wesołowski, Cierpiała 2011). Soil packing has a negative effect on physical properties (Aikins, Afuakwa 2012), as well as chemical and biological characteristics of soil (Ernst, Emmerling 2009, Abdollahi, Munkholm 2014). Compacted soil inhibits root formation by plants, water percolation, transfer of mineral compounds and permeation of air through the soil, resulting in lower yields of crops (Morris et al. 2010, Małecka et al. 2012).

A possible way to counteract soil compaction is to implement such technologies that will reduce the intensity and depth of soil tillage treatments (Biskupski et al. 2009, Wesołowski, Cierpiała 2011).

The research results suggest that the above approach can limit the soil compaction (Wesołowski, Cierpiała 2011) and have a positive effect on the soil chemical and biological properties, including the number and biomass of Lumbricidae (Blecharczyk et al. 2007, Małecka et al. 2007, Abdollahi, Munkholm 2014). Edwards (1984) showed that there were about 50 pcs earthworms on average per 1 m^2 in a 15-cm deep soil horizon following shallower soil tillage treatments, which contrasted with the complete absence of earthworms in soil after conventional ploughing. This situation may have a significant influence on the direction and outcome of organic matter metabolism, as well as the abundance and activity of soil microflora in agricultural ecosystems, which eventually would affect the soil fertility. Another factor which influences soil chemical and biological characteristics, beside soil tillage, is the selection of crops for a crop rotation sequence. Winter oilseed rape is a very good choice as it elevates the amount of humus and the content of nutrients in soil, as well as creating suitable conditions for the growth and development of useful soil fauna.

The aim of this study has been to determine the effect of compaction and different soil tillage systems on changes in chemical properties of soil, and on the number of biomass of Lumbricidae in soil cropped with two cultivars of oilseed rape.

MATERIALS AND METHODS

The research results were obtained from a controlled, long-term, two-factorial field experiment, carried out in Bałcyny (53°36′ N, 19°51′ E), an experimental station of the University of Warmia and Mazury in Olsztyn (Poland). The experiment was set up in a random block design with 4 replications. There were 32 plots, each of the size of 30 m^2. The experiment was established on a Haplic Luvisol (Aric, Ochric) originated from loamy sand (LS) underlain by sandy loam (SL – Working Group WRB (2015). The topmost soil horizon (0-20 cm) contained from 10.0 to 10.7 g kg^{-1} of organic carbon, had an acid to slightly acid reaction (pH_{KCl} 5.4-5.6), and the following content of basic nutrients: 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 abundance).

The research compared 4 soil tillage systems in a three-field crop rotation: winter oilseed rape (OSR) – winter wheat – spring barley. The oilseed rape sown in the first crop rotation was cv. Californium (double-low line variety), while the second crop rotation was started by sowing seeds of the variety Mendel F_1.

The experimental factors comprised:

1 – degree of pre-sowing compaction of soil:

- control variant without compaction;

- a variant with soil compaction after harvesting the preceding crop. Soil packing was achieved through the passage of a tractor and trailer weighing *ca* 6 tonnes and moving trace by trace. The preceding crop for both OSR varieties was spring barley;

2 – four different ways of preparing a field for sowing the test plant.

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

Winter oilseed rape (OSR) of the varieties Californum and Mendel was sown on the same date, that is on 12 August 2008 and 2011, in a dose of 5.0 kg ha^{-1}. Fertilisation consisted of mineral fertilisers NPK only, and these were applied in the following doses (kg ha^{-1}): N – 180.0, P – 35.0 i K – 100.0. Sowing the crops on all plots was performed with a combine sowing machine and cultivator manufactured by Väderstad. Plant protection chemicals were applied depending on the severity of infestation by agrophages. Oilseed rape was harvested at the full maturity of seeds (BBCH 87-89).

Table 1

Choice and sequence of soil tillage treatments before sowing of winter oilseed rape

Soil tillage system	Conventional tillage – control object U - 1	Tillage U-2	Tillage U-3	Tillage U-4
After harvest	shallow ploughing 10 cm + harrowing	chisel (40 cm) + disk cultivator + harrowing + cultivating	shallow ploughing 10 cm + harrowing	-
Before harvest	pre-sowing ploughing 20 cm	pre-sowing ploughing 20 cm	-	single ploughing 30 cm

Soil samples for chemical analyses were collected in the spring of 2008 (before the experiment was commenced) and before the harvest of both varieties of (BBCH 87-89), i.e. in 2009 and in 2012. Samples were taken from the 0-20 cm soil layer, from each plot at 4 fixed sites. Soil samples underwent determination of the reaction (1 mol KCl), content of C org, N og and phytoavailable forms of phosphorus, potassium and magnesium. The soil reaction was determined by potentiometry, organic carbon – with the spectrophotometric method, total nitrogen – by flame photometry, and magnesium – by flame atomic absorption spectrometry. All analyses were made in a certified laboratory of the Agricultural Chemistry Station in Olsztyn.

Earthworms were extraxcted from soil using 0.4% solution of formalin, which was poured over the plots after all plant residue had been removed. Soil samples were collected from oilseed rape plots on two dates (after plant emergence and before harvest) from an area of 0.25 m^2 and at a depth of around 20 cm, at fixed sites on each plot. Next, in a laboratory, earthworms were rinsed 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 (KASPRZAK 1986). All data were converted to a surface area of $1m^2$.

The results were submitted to statistical processing. First, the Shapiro--Wilk's normality test at p<0.05 was applied, demonstrating that the number and mass of eartworms did not satisfy the parameters of normal distribution. Thus, to evaluate the significance of differences between the tested reduced tillage systems and conventional soil cultivation as well as between plots with and without soil compaction, the non-parametric U Mann-Whitney's test was used, at the level of significance equal α=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 two oilseed rape varieties. The assessment of correlations between the number and mass of earthworms and the chemical properties of soil relied on the Spearman's rank-order correlation coefficients. All calculations were supported by Statistica® 13 (TIBCO Software Inc. 2017).

During the growing season of 2008/2009, and specifically during the autumn growth of winter oilseed rape (OSR), the sum of atmospheric precipitation exceeded by 36.4 mm the average values over a multi-year period (Table 2). August and October proved to be extremely wet (103.1 and 104.6 mm), but the rainfall total in September was nearly 3.5-fold lower than the long-term average.

During the spring and summer plant growth (from March to July 2008/2009), the total rainfall (376.6) exceeded average values from many years. In April, soil was found to be dry (3.7 mm of rainfall). In May and June, the total precipitation was almost 1.5- and nearly 2-fold higher, respectively, than the analogous multi-year average amounts. Also, July that year was noted to be wetter than the average recorded in the vicinity of the village Bałcyny.

Table 2

Values of temperature and atmospheric precipitation during the growing season of winter oilseed rape (from August to July)

Years	Months								Total/ /sum/mean VIII-X	Total/ /sum/mean III-VII
	Aug VIII	Sept IX	Oct X	March III	Apr IV	May V	June VI	July VII		
Precipitation (mm)										
2008/2009	103.1	17.0	104.6	68.0	3.7	89.6	133.1	82.2	224.7	376.6
2011/2012	83.6	38.9	29.9	13.6	44.7	42.5	107.2	112.2	152.4	320.2
1962-2002	75.2	59.1	54.0	28.5	35.4	57.6	69.5	81.6	188.3	244.1
Mean air temperature (°C)										
2008/2009	17.7	11.9	8.6	1.9	9.7	12.2	14.7	18.9	12.7	11.5
2011/2012	18.1	14.6	8.6	3.5	8.4	13.9	15.2	19.0	13.8	12.0
1962-2002	16.8	12.6	8.1	1.4	7.0	12.5	15.8	17.2	12.5	13.1

In 2011/2012, the total precipitation from August to October corresponded to 80% of the multi-year average sum. In October, the amount of rainfall was barely half the average rainfall noted over many years. During the spring and summer plant growth, from March to July 2011/2012) total precipitation (320.2 mm) were above the multi-year average data. In April, the sum of rainfalls was by 9.3 mm higher than the multi-year average, but May was quite dry (42.5 mm of rain), whereas June and July were very wet, and the sum of rainfall in these months, compared to the multi-year average data recorded near Bałcyny, was higher by 37.7 and 30.6 mm, repectively.

RESULTS

The experimental factors differentiated the soil reaction and its content of available nutrients in the 0-20 cm soil horizon. After the harvest of winter oilseed rape (cv. Californium) in 2009, the soil reaction on plots with and without compaction was within the range of 5.56 to 6.00. A rise in the soil pH observed on the plots with single ploughing was significant relative to the analogous cultivation on plots with soil compaction (Table 3). On plots with soil compaction, compared to plots without compaction, significantly less organic carbon (by 11.8% on average) was determined than in soil submitted to the reduced cultivation U-2 system.

Abandoning post-harvest soil tillage and performing a single ploughing treatment (plots with soil compaction) significantly increased the concentration of available phosphorus in comparison with the analogous cultivation system without soil compaction. After the ploughing and the shallow ploughing U-2 soil tillage systems, a reverse situation was noted, namely more P

Table 3

Chemical properties of soil before harvest of winter oilseed rape cv. Californium and Mendel

Chemical proper-ties	Tillage methods*	Californium		p	Mendel		p
		degree of soil compaction			degree of soil compaction		
		A $\bar{x}$ ± s	B $\bar{x}$ ± s		A $\bar{x}$ ± s	B $\bar{x}$ ± s	
pH	U-1	5.60 ± 0.35	5.69 ± 0.11	0.642	5.75 ± 0.35	5.66 ± 0.14	0.660
	U-2	5.66 ± 0.24	5.56 ± 0.12	0.460	5.84 ± 0.42	5.54 ± 0.07	0.208
	U-3	6.00 ± 0.05	5.91 ± 0.06	0.061	5.85 ± 0.21	5.74 ± 0.17	0.441
	U-4	5.86 ± 0.13	5.65 ± 0.05	0.024	5.87 ± 0.16	5.63 ± 0.03	0.027
C org (g kg^{-1})	U-1	10.3 ± 0.71	9.38 ± 0.75	0.122	10.4 ± 0.80	9.50 ± 0.71	0.152
	U-2	10.6 ± 0.31	9.35 ± 0.47	0.004	10.7 ± 0.28	9.33 ± 0.53	0.004
	U-3	10.4 ± 0.92	9.38 ± 1.38	0.252	10.4 ± 1.07	9.15 ± 0.93	0.134
	U-4	9.98 ± 0.66	8.88 ± 0.57	0.045	9.83 ± 0.79	8.70 ± 0.62	0.066
N (g kg^{-1})	U-1	0.81 ± 0.15	0.83 ± 0.08	0.849	0.79 ± 0.17	0.82 ± 0.09	0.800
	U-2	0.84 ± 0.09	0.86 ± 0.03	0.734	0.82 ± 0.09	0.89 ± 0.05	0.208
	U-3	0.80 ± 0.07	0.88 ± 0.14	0.339	0.79 ± 0.07	0.69 ± 0.11	0.172
	U-4	0.88 ± 0.13	0.84 ± 0.04	0.568	0.82 ± 0.16	0.81 ± 0.07	0.934
C:N	U-1	13.0 ± 2.23	11.4 ± 1.85	0.322	13.8 ± 4.28	11.8 ± 1.87	0.428
	U-2	12.8 ± 1.64	10.9 ± 0.64	0.078	13.2 ± 1.72	10.5 ± 0.84	0.030
	U-3	13.1 ± 1.36	10.7 ± 1.44	0.055	13.2 ± 1.57	13.7 ± 3.54	0.802
	U-4	11.5 ± 1.91	10.5 ± 0.70	0.389	12.3 ± 2.45	10.8 ± 0.79	0.268
P (mg kg^{-1})	U-1	78.8 ± 1.24	75.2 ± 0.48	0.001	78.3 ± 1.62	75.7 ± 0.83	0.028
	U-2	78.2 ± 0.93	73.6 ± 2.31	0.010	78.1 ± 1.35	74.1 ± 0.61	0.002
	U-3	77.5 ± 1.78	81.0 ± 2.50	0.065	75.8 ± 0.90	79.4 ± 1.27	0.004
	U-4	78.9 ± 2.33	83.2 ± 0.65	0.012	78.7 ± 2.34	82.8 ± 1.18	0.021
K (mg kg^{-1})	U-1	121 ± 1.74	146 ± 6.01	<0.001	120 ± 1.37	149 ± 0.46	<0.001
	U-2	98.3 ± 1.39	117 ± 1.63	<0.001	98.8 ± 1.66	118 ± 0.60	<0.001
	U-3	130 ± 1.02	165 ± 1.28	<0.001	129 ± 1.61	164 ± 1.35	<0.001
	U-4	107 ± 4.99	158 ± 3.32	<0.001	106 ± 5.12	157 ± 3.44	<0.001
Mg (mg kg^{-1})	U-1	38.2 ± 1.18	38.9 ± 1.57	0.475	38.0 ± 1.44	38.0 ± 0.71	0.976
	U-2	36.4 ± 1.05	35.5 ± 2.61	0.546	36.1 ± 0.86	35.1 ± 2.48	0.454
	U-3	37.8 ± 1.32	39.8 ± 0.32	0.026	36.3 ± 0.15	39.2 ± 0.50	<0.001
	U-4	39.9 ± 0.15	39.2 ± 0.70	0.091	39.8 ± 0.15	38.1 ± 0.70	0.003

* Explanation see Table 1, A – without compaction, B – with compaction, $\bar{x}$ ± s – mean ± standard deviation, p – t-Student test probability

was detected in soil from plots without soil compaction. The tested soil tillage systems significantly raised the content of available K in plots with compaction, compared to plots without soil compaction, and the biggest difference was observed following single ploughing (U-4 system).

Both the degree of soil compaction and the soil tillage systems significantly varied the content of nutrients in oilseed rape (cv. Mendel) grown after 3 years of a crop rotation system. In both variants (with and without soil compaction) soil reaction was slighly acidic (pH from 5.54 to 5.87). Single ploughing (U-4 tillage system) decreased significantly the soil pH in plots with soil compaction in comparison with the analogous cultivation variant without soil compaction. Similar relationships were noted after U-2 cultivation with respect to the content of organic carbon in soil and the C:N ratio. A significantly higher concentration of available P (by 4.7% on average) was determined in the soil from plots with soil compaction undergoing single ploughing and shallow ploughing U-3, compared to the analogous variants of soil tillage without soil compaction, although when the complete ploughing tillage system (control) as well as deep and sowing ploughing to a 20 cm depth (U-2 variant) were performed, contrary findings were achieved. The soil tillage variants tested in the experiment resulted in a higher content of available K in soil from the plots with soil compaction than in the ones without compaction, and the highest difference in the content of this element in soil (51.0 m kg^{-1}) was revealed after a single ploughing treatment had been implemented (U-4 tillage system). In turn, the content of available Mg in soil was significantly increased owing to the application of shallow ploughing in the set of post-harvest soil tillage treatments (U-3 variant) on plots with soil compaction, whereas variant U-4 (single ploughing) caused a reverse effect.

The experimental factors caused differences in the number and biomass of earthworms in soil under winter oilseed rape (cv. Californium) in 2008. Once the plants emerged, there were nearly twice as many earthworms in plots without compaction as in plots where soil had been compacted (Table 4). By abandoning post-harvest tillage treatments and applying a single ploughing (plots withut compaction) – compared to the analogous treatments on compacted plots – the number of Lumbricidae increased by 73% and their mass more than doubled. Similarly, significantly higher values of the analysed features were observed after ploughing (control object). Shallow ploughing and harrowing of a field (variant U-3) raised the density of earthworms by 52.3% (plots without soil packing), but resulted in a nearly 1.5-fold decrease in their biomass in plots with soil compaction. After the emergence of plants (plots with compaction), the tillage variants U-4 and U-3 significantly increased the number of earthworms compared with the conventional ploughing system (control), and a significant rise in the biomass of earthworms was observed in variants U-3 and U-4 (plots without compaction), as well as U-2, U-3 and U-4 (plots with soil packing after crop cultivation).

Table 4

Number per 1m² and biomass (g m²) of earthworms after plant emergence and before winter OSR harvest

Tillage methods*	Degre of soil compaction		p	Degre 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 OSR – cv. Californium					
U-1	4.50±1.29	2.75±0.50	0.045	2.70±0.34	0.95±0.29	<0.0001
U-2	4.00±1.63	4.50±1.29	0.648	2.07 ±0.41	3.34±0.24	0.002
U-3	5.75±1.50	2.75±0.96	0.019	1.87 ±0.32	2.71±0.13	0.008
U-4	6.50±2.38	1.75±0.50	0.023	5.01±0.77	2.33±0.08	0.006
	number before harvest			mass before harvest		
U-1	5.75±1.89	6.75±1.71	0.463	4.62±0.46	4.95±0.19	0.232
U-2	4.50±1.00	5.00±0.82	0.468	3.49±0.50	2.95±0.30	0.110
U-3	4.25±3.59	5.75±0.50	0.655	5.98±0.33	4.53±0.39	0.001
U-4	3.75±0.96	8.25±2.75	0.040	2.61±0.50	6.29±0.19	<0.0001
Winter OSR – cv. Mendel						
	number after emergence			mass after emergence		
U-1	3.00±0.82	2.25±0.96	0.2782	2.40±0.12	0.79±0.29	<0.0001
U-2	3.75±1.71	6.25±2.50	0.1500	1.93±0.54	3.20±0.34	0.0070
U-3	2.50±0.58	5.25±1.71	0.0225	1.72±0.27	2.31±0.16	0.0091
U-4	6.00±2.16	2.25±0.96	0.0192	4.80±0.88	2.11±0.10	0.0009
	number before harvest			mass before harvest		
U-1	5.00±2.16	7.25±3.20	0.2882	4.29±0.62	4.83±0.90	0.3567
U-2	4.75±1.89	4.25±2.50	0.7606	3.29±0.68	2.80±0.37	0.2461
U-3	7.50±4.80	5.25±1.71	0.4107	5.80±0.54	4.44±0.48	0.0096
U-4	3.00±1.41	7.00±2.16	0.0212	2.25±0.10	6.61±0.47	<0.0001

* Explanation see table 1, A – without compaction, B – with compaction, $\bar{x} \pm s$ – mean ±standard deviation, p – U Mann-Whitney's test probability (significant $p<0.05$)

Prior to the harvest of winter oilseed rape cv. Califorium, in comparison with the results of the evaluation carried out after plant emergence (plots without compaction), the number of earthworms was smaller by over 12%, while being twice as high on compacted plots. In the experimental plots (with or without compaction), the biomass of earthworms was from 1.5- to 2-fold higher. Single ploughing (plots with compaction) neraly doubled the number of Lubricidae and raised their biomass by nearly 2.5-fold in comparison with the analogous tillage on plots without soil compaction. In turn, the tillage system U-3 (plots without compaction) resulted in an over 24% higher biomass of earthworms in soil. The U-2 and U-4 tillage systems (plots with compaction) significantly increased the biomass of earthworms relative to the findings in the control variants (ploughing tillage), whereas among the plots without compaction a similar effect was observed after the implementation of the U-2, U-3 and U-4 tillage systems (Table 5).

After the emergence of winter oilseed rape (cv. Mendel) grown on the same field three years into a crop rotation cycle, the density of earthworms per surface unit was by 4.4% higher on plots with compaction than without compaction (Table 4). Soil tillage U-3 (plots with compaction) more than doubled the number of Lumbricidae compared to the analogous cultivation variant on uncompacted plots. In turn, over 62% more speciemens of this species were observed on uncompacted plots with a single ploughing, which raised the number of earthworms to the highest degree compared with the control ploughing system (Table 5). The conventional ploughing and

Table 5

Comparison of the number and mass of earthworms in reduced tillage systems after emergence and before harvest of winter oilseed rape

Tillage methods*	Degre of soil compaction			
	A	B	A	B
	winter OSR – cv. Californium – after emergence			
	number		mass	
U-1	x	x	x	x
U-2	ns	*	ns	**
U-3	ns	ns	*	**
U-4	ns	*	**	**
Winter OSR – cv. Californium – before harvest				
U-1	x	x	x	x
U-2	ns	ns	*	**
U-3	ns	ns	**	ns
U-4	ns	ns	**	**
Winter OSR – cv. Mendel – after emergence				
U-1	x	x	x	x
U-2	ns	*	ns	**
U-3	ns	*	**	**
U-4	*	ns	**	**
Winter OSR – cv. Mendel – before harvest				
U-1	x	x	x	x
U-2	ns	ns	ns	**
U-3	ns	ns	*	ns
U-4	ns	ns	**	*

* Explanation – see Table 1, A – without soil compaction, B – with soil compaction, ns – non-significant value, ^{x} significance at p<0.05, ^{xx} significance at p<0.01

reduced U-4 tillage (plots with compaction), relative to the analogous treatments on plots without soil compaction, decreased the biomass of earthworms by 67 and 56%, respectively, although a contrary situation was observed following the soil tillage systems U-2 and U-3 (mass of individuals was higher by 39.6 and 25.6%).

Before the harvest of OSR cv. Mendel (in 2012), there were more earthworms on the plots with or without soil compaction, with their number higher by 24.6 and 32.8% than after the plant emergence. A single ploughing treatment (plots with compaction) significantly raised the number (by 57.0%) and nearly trebled the biomass of Lumbricidae in the analysed topsoil compared with the analogous variant on plots without soil compaction. In turn, a significantly higher mass of earthworms was determined after the soil tillage variant U-3 among the plots without compaction. Soil tillage technologies U-4 (plots with compaction) significantly increased the biomass of earthworms compared with the conventional ploughing system (control), and a similar effect was observed on plots without compaction following the implementation of U-3 tillage variants (Tables 4 and 5).

The analysis of correlations demonstrated that there was a statistically significant positive correlation between the biomass of Lumbricidae and the soil pH only in the variant with ploughing (control) before harvest (plots with compaction) – Table 6.

A similar character of dependences was noticed between the number of earthworms and the soil richness in nitrogen and phosphorus after U-4 soil tillage system (plots without compaction). However, after the U-2 and U-4 variants had been carried out (plots with compaction), the outcome was opposite, i.e. there was an increase in the content of nitrogen only in U-2, and in phosphorus and potassium only in U-4, but the number of earthworms per surface area unit decreased significantly. Following a single ploughing treatment (plots with compaction), it was found that a greater soil nitrogen content correlated significantly with a greater number of earthworms. After the conventional ploughing technology (plots without compaction), a positive correlation was determined between the soil Mg content and the biomass of Lumbricidae, while a reverse dependence was observed on compacted plots after a single ploughing.

DISCUSSION

Different soil tillage systems can lead to changes in the soil content of nutrients and cause variation in the soil reaction. In our study, the traditional ploughing system, under either of the tested OSR cultivars, did not change significantly the pH of soil, which remained on an approximately same level (pH 5.60 to 5.75), whereas a significant increase in the analysed

Table 6

Spearman's rank correlation coefficients between number and biomass of earthworms and chemical properties of soil

Tillage method	pH	C org.	Total N	P	K	Mg
	number of earthworms before winter oilseed rape harvest – plots without soil compaction					
U-1	-0.45	-0.21	-0.33	0.03	-0.49	-0.48
U-2	-0.63	-0.10	-0.15	-0.37	0.06	-0.09
U-3	-0.32	-0.43	0.34	-0.39	0.27	-0.32
U-4	0.20	0.65	0.78[x]	0.90[xx]	0.65	-0.09
Number of earthworms before winter oilseed rape harvest– plots with soil compaction						
U-1	0.47	0.29	0.14	-0.15	0.10	0.45
U-2	-0.27	-0.40	-0.71[x]	0.35	0.15	-0.61
U-3	-0.28	-0.10	0.24	-0.37	0.28	-0.22
U-4	0.53	0.79[x]	0.56	-0.74[x]	-0.72[x]	0.33
Mass of earthworms before winter oilseed rape harvest– plots without soil compaction						
U-1	-0.40	-0.48	-0.23	0.37	-0.31	0.87[xx]
U-2	0.18	0.17	0.20	0.66	-0.35	-0.23
U-3	0.53	0.48	-0.16	-0.37	0.11	0.38
U-4	-0.34	-0.55	-0.59	-0.38	-0.10	0.60
Mass of earthworms before winter oilseed rape harvest– plots with soil compaction						
U-1	0.79[x]	0.55	-0.38	-0.23	0.55	-0.33
U-2	-0.05	0.41	0.47	-0.25	0.19	0.68
U-3	-0.22	-0.19	0.25	-0.28	0.43	0.15
U-4	-0.01	-0.56	0.38	0.08	0.18	-0.75[x]

[x] significant at $p<0.05$, [xx] significant at $p<0.01$

trait was observed after a single ploughing (U-4 variant) under cv. Californium and cv. Mendel (plots with compaction). To some extent, these results correspond with the ones obtained by Małecka et al. (2007), who proved that the soil reaction remained on a similar level after the traditional soil tillage system, but when a stubble cultivator was used the soil pH decreased slightly (by 0.2-0.3 unit). Blecharczyk et al. (2007) demonstrated that soil tillage systems differentiated the soil reaction and its available phosphorus content to a lesser extent, and slightly more phosphorus was determined in the topsoil. These authors 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. Likewise, Małecka et al. (2007) noted a larger content of organic carbon (by 17.7%) and total nitrogen (by 9.9%) in a reduced tillage system compared with the traditional one. Soil submitted to reduced tillage was characterised by a higher content of macroelements, especially potassium, where an increase relative to the ploughing system reached 50%.

Somewhat different results were achieved in our study, where the U-2 soil tillage variant under both winter oilseed rape varieties (plots with compaction) raised the C organic content in soil relative to the analogous tillage systen with soil compaction. Single ploughing (plots with compaction) significantly increased the concentration of available phosphorus compared to the analogous cultivation variant on plots without soil compaction. After the conventional ploughing system as well as shallow ploughing (U-2), a reverse outcome was documented. The tested soil tillage technologies significantly increased the content of available K on plots with soil compaction, and the highest significant difference was observed after single ploughing (U-4).

The degree of soil compaction and the different soil tillage technologies differentiated the soil richness in available nutrients in oilseed rape plants (cv. Mendel) grown three years into a crop rotation sequence. The U-2 soil tillage method on plots with soil compaction decreased the content of organic carbon and the C:N ratio in soil. The plots with soil compaction submitted to the single ploughing and shallow ploughing U-3 soil tillage technologies were found to contain more available P in soil than in the plots undergoing the analogous soil tillage variants without soil compaction, whereas a reverse situation was observed after the complete ploughing technology (control) and the reduced tillage U-2 system. The soil tillage systems tested in the experiment significantly increased the content of available K on plots with compaction in comparison with the soil in uncompacted plots.

In general, every agricultural technology leads to some distrubance of the soil's biological balance, and soil tillage has an exceptionally unfavourable influence on the species composition, number and biomass of soil organisms (URMLER 2010, FLOHRE et al. 2011).

KUNTZ et al. (2013) documented the fact that reduced soil tillage raised the number of earthworms by 67% and their biomass by 48% compared with the ploughing tillage method. LENART and SŁAWIŃSKI (2010) claim that values of these features are higher in the autumn then in the spring. Similar results were recorded by CURRY et al. (2002), JORDAN et al. (2004) and METZKE et al. (2007). In our experiment, the tested factors determined the density and biomass of Lumbricidae in the analysed soil horizon and on the sampling dates. After emergence of oilseed rape plants (cv. Californicum) on plots without compaction, the number of earthworms was nearly twice as high. Single ploughing of plots without soil compaction raised by 73% the number of Lumbricidae and more than doubled their mass. Likewise, significantly higher values of the analysed parameters were observed in the ploughing system (the control variant). Before the harvest of winter oilseed rape cv. Californium, in comparison with the assessment made after plant emergence (plots without compaction), the number of earthworms was smaller by over 12%, while being twice as high on plots with compaction. Single ploughing (plots with soil compaction) more than doubled the number of Lumbricidae and raised their mass by nearly 2.5-fold relative to the analogous treatments on plots without compaction of soil. The soil tillage systems U-2 and U-4 (plots with compaction) significantly increased the mass of earthworms in comparison with the ploughing tillage system (the control), whereas on plots without compaction a similar effect was observed after the implementation of U-2, U-3 or U-4 systems. Following the emergence of winter oilseed rape (cv. Mendel), the U-2 tillage system (plots with compaction) caused an over 2-fold increase in the number of Lumbricidae in comparison with the analogous tillage variant on uncompacted plots. On the plots without soil compaction it was a single ploughing that raised the number of earthworms the highest relative to the ploughing tillage. A similar effect was noted on plots with soil compaction submitted to the tillage systems U-3 and U-2.

Before harvesting winter oilseed rape of the variety Mendel, the number of earthworms on plots with and without soil compaction was by 32.8% and 24.6% higher than determined after the emergence of the crop. Single ploughing on plots with soil compaction increased by 57% the density of earthworms and nearly trebled their mass compared to the determinations made after the emergence of oilseed rape plants. The tillage systems U-4 (plots with compaction) as well as U-3 (plots without compaction) resulted in a significant increase in the biomass of earthworms relative to the ploughing soil tillage (control) system.

Westernacher-Dotzler (1992) report that from 29% to 50% of earthworms die directly due to a soil tillage treatment, while another 39% disappear as the soil becomes excessively dry. Crittenden et al. (2014) demonstrated that the ploughing and reduced tillage systems can decrease considerably the density of Lumbricidae over the 21 days following a ploughing treatment in the autumn, but in the spring next year the population of earthworms regains its original state and no significant differences are observed between the ploughing and reduced tillage systems. In contrast, Curry et al. (2002) claim that any drastic methods of soil tillage can eliminate a whole population of earthworms in just one plant growing season. Chan (2001) maintain that earthworms which penetrate deeper into soil respond to traditional soil tillage by a greater decrease in their number.

In our study, a correlation was determined between the soil richness in nutrients and the number of Lumbricidae. A higher content of N and P in soil after a single ploughing (plots without compaction) significantly correlated with the density of earthworms, whereas subsequent to the tillage methods U-2 and U-4 (plots with compaction) an increase in the soil content of nitrogen, phosphorus and potassium coincided with a decrease in the density of earthworms. A single ploughing raised the soil content of organic C, to which Lumbricidae responded by their growing number. The analysis of correlations demonstrated a statistically significant positive correlation between the mass of Lumbricidae and the soil pH only after the ploughing soil tillage system (plots with soil compaction). Szulac and Dubas (2007) noted that when a reduced soil tillage method was implemented, the content of C in soil was strongly positively correlated with the population of earthworms, although such correlations were not determined in soil submitted to a conventional ploughing system.

Ogle et al. (2005) as well as Chatterjee and Lal (2009) claim that the range of changes induced in soil by soil tillage (including all kinds of reduced tillage) is strongly dependent on on the amount and distribution of rainfall, thermal conditions, soil type and fertilisation, while Schmidt and Curry (2001) maintain that the species composition, biomass and abundance of earthworms are also influenced by the selection of crops for a crop rotation system.

Studies completed to this day fail to provide a definite answer as to how reduced tillage affects the living habitat of soil organisms (Szulc, Dubas 2007, Felten, Emmerling 2011, Crittenden et al. 2014). It is therefore essential to continue research on populations of Lumbricidae, and in the future to try and limit the acreage of fields where traditional, ploughing systems are implemeneted for the benefit of a broader use of reduced tillage systems. It is equally important to select optimal solutions being guided by the specific features of habitats, knowledge of needs of cultivated crops, and the technical equipment on farms.

CONCLUSIONS

1. The reduced soil tillage variant U-4, under both tested winter oilseed rape varieties, decreased the soil content of organic carbon while increasing its pool of available phosphorus in comparison with the traditional ploughing system (control). A similar situation was observed in the case of available K after the superficial tillage system U-3. Under winter OSR (cv. Mendel), three years into a given crop rotation, the tillage method U-2 (subsoiler, disc harrow, cultivator + pre-sowing ploughing to 20 cm) caused a reverse effect.

2. After emergence of oilseed rape (cv. Californium), the U-4 tillage method (plot without compaction), in relation to the analogous treatments on soil compacted plots, increased the number by 73% and more than doubled the mass earthworms, while the U-3 method (compacted plots) lowered their biomass by nearly 1.5-fold. On plots with soil compaction, the tillage variants U-4 and U-2 significantly increased the number of earthworms compared with the ploughing system, and a significant rise in the biomass of earthworms (plots without compaction) was noted after the tillage variants U-4, and on compacted plots – after U-2, U-3 and U-4 system.

3. There were fewer earthworms on plots without compaction prior to the harvest of oilseed rape cv. Californium in comparison with the determinations made after the emergence of plants, in contrast to plots with soil compaction, where the number of Lumbricidae nearly doubled and their biomass was almost 2.5-fold higher compared with the analogous treatments on plots without soil compaction. Before harvest the tillage method U-4 (plots with compaction) significantly increased the mass of earthworms in relation to the ploughing tillage (control object), whereas a similar situation was observed on plots without compaction after the tillage U-3.

4. After plant emergence (cv. Mendel), the U-3 tillage variant (plots with compaction) more than doubled the number of Lumbricidae, in relation to the analogous cultivation on uncompacted plots. On plots without compaction over 62% more earthworms were found after a single ploughing treatment, which caused the highest increase in the number of earthworms relative to the ploughing tillage method (control).

5. After the traditional ploughing tillage system (control), the increase in soil reaction significantly positively correlated with the biomass of earthworms in the topsoil. Similar dependences were detected in number of earthworms when the soil content of nitrogen and phosphorus increased after the soil tillage method U-4 (plots without compaction). When the soil content of nitrogen in U-2 tillage method 4 (compacted plots), phosphorus and potassium in U-4 method 4 (compacted plots) increased, the number of earthworms in the topmost soil horison significantly decreased. A greater content of carbon in soil after a single ploughing treatment significantly increased the density of earthworms.

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