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ORIGINAL PAPER

EFFECT OF A TILLAGE SYSTEM ON THE CHEMICAL PROPERTIES OF SANDY LOAM SOILS*

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Abstract

A tillage system can affect significantly the concentration of some heavy metals and their availability to plants which grow on the tilled soil. The purpose of this study has been to determine the impact of different tillage systems on the chemical properties of arable sandy loam soils under the same crop rotation, organic residue management and mineral fertilization. A single-treatment field experiment in a randomised block design was performed on sandy loam soils. Four-year tillage study data were compiled and compared with respect to full-inversion tillage (FIT), strip-till (ST) and reduced tillage (RT) systems. Soil samples were mineralised in a mixture of HF and $HClO_4$ acids to determine the total content of metals. Total organic carbon (TOC) and total nitrogen (N_t) were also assayed. The content of available metal forms was determined using diethylene triamine pentaacetic acid (DTPA). The soil maintained in the FIT system contained significantly more Zn and Fe available to plants than the soil cultivated according to the RT and ST systems. The FIT and ST systems decreased the total Zn, Cu, Mn and Fe content in soil significantly compared with the RT system. Relative accumulation of the heavy metals at the depth of 30-50 cm can be related to the distribution of the clay fraction in soil profiles. In the topsoil (0-30 cm), the average content of TOC was significantly higher under the RT than under FIT and ST systems. The results confirm that a tillage system is one of the factors affecting the content of heavy metals, TOC accumulation and heavy metal distribution in sandy loam soils, although the pedogenic processes determining the quality of arable soils quality must be considered as well.

Keywords: tillage system, field experiment, microelements, sandy loam soil.

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INTRODUCTION

Intensive agricultural management, also known as intensive farming, is often responsible for deterioration of the soil quality. This applies to arable soils in Poland, which – because of their origin – are predominantly rather poor in macro- and micronutrients as well as humus. Sandy loam soils are often deficient in micronutrients and can require additional fertilization to maintain optimal plant growth and to achieve high crop yields. *Soil quality* relies on good soil management. Evaluating the effect of agricultural management practices on chemical properties and the related quality of cultivated soils remains an important task (Jaskulska et al. 2014, van Eerd et al. 2014, Gajda et al. 2017). The total content of trace elements in soil has an essential impact on the amount of metals available to plants, albeit depending on soil properties (Baldantoni et al. 2010). Soil management practices, such as organic and mineral fertilization and crop residue retention, enhance metal accumulation in the topsoil, thus limiting metal translocation deep down the soil profile (Lamy et al. 2006). Of all the methods for determination of amounts of heavy metals, the most important are the ones which facilitate assessment of their content of forms available to plants. Various extractants are used in different laboratories to assess the content of mobile forms of heavy metals in soils (potentially available for plant), for example neutral salts (0.1 M $NaNO_3$, 0.01 M $CaCl_2$, 1 M NH_4NO_3), diluted acids (2.5% CH_3COOH, 0.1 M HCl), buffer (CH_3COONH_4), and chelating agents, DTPA and EDTA (Hammer, Keller 2002, Feng et al. 2005, Dinić et al. 2019). Local environmental conditions and the key properties of soil, especially pH, texture, clay minerals and organic matter, affect the solubility of trace elements and their availability to plants (Dabkowska-Naskret 2003, Grüter et al. 2017). According to some scientists, e.g. Chantigny (2003), Dębska et al. (2012), Balík et al. (2018) and Si et al. (2018), fertilization, crop rotation and tillage treatments are the factors significantly affecting the content of organic matter in agricultural soils. The concept of conservation tillage has been gaining popularity over the recent years, as a solution in sustainable agriculture (Busari et al. 2015). In the strip-till (ST) system, soil is not fully inverted during tillage operations and 60-75% of post-harvest residue remain on the field surface, in the disturbed surface horizon (Morris et al. 2010). After a few years of the ST treatment, an increased content of soil organic carbon (SOM) is observed, especially in the topsoil (Fernández et al. 2015). The loss of soil organic matter, soil structure deterioration, as well as lowered water holding capacity due to soil erosion induced by tillage affect soil productivity.

The aim of the study has been to assess the impact of tillage systems on the content of total and mobile forms of heavy metals and the SOM content in soils under the same crop rotation system and fertilisation regime. The main purpose was to verify whether tillage systems could influence the heavy metal distribution in the surface and subsurface layer of soils.

MATERIAL AND METHODS

Field trial

In 2012-2016, a field experiment was conducted on a farm in the village Śmielin (Figure 1), in central Poland (53°09′04″N, 17°29′11″E). This single-

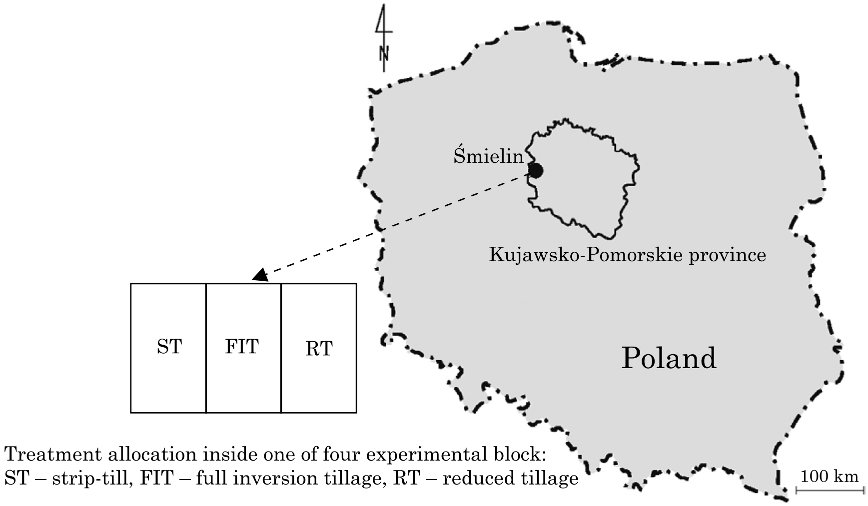

Fig. 1. Location of the experimental field site

-treatment field experiment in a randomised block design was set up on sandy loam soils. The plot size was 250 x12 m, and there were four replications. The area where the field experiment was set up was characterised by low precipitation, around 500 mm on average. The following fertilization was applied to all the experimental plots every year: 150-170 kg N ha^{-1}, 60-80 kg P_2O_5 ha^{-1} and 90-120 kg K_2O ha^{-1}. The experimental factor (A) included the type of soil tillage for a winter rapeseed – winter wheat crop rotation, with four replications:

- reduced tillage (RT); loosening of soil and straw application (cultivator Horsch Tiger 4 AS). Pre-sowing mineral fertilization over the entire fields (Amazone ZG-TS 8200 trailed spreader). Seedbed was prepared for seeding, followed by high-precision seeding, all in one passage of a seeding machine (Horsch Pronto 4DC);
- strip-till (ST) – tillage of only thin strips of soil, applying fertilizers over the whole strip, placing seeds in it, at a fixed depth. A Mzuri Pro-Til 4T machine was used to ensure tillage, fertilization and sowing in one passage of the equipment directly over a stubble field. A Mzuri Pro-Til 4T machine is a four-meter unit for strip-till soil cultivation, equipped with 11 rows of drill coulters which sow seeds in 36.3 cm wide intervals;

– full inversion tillage (FIT); the *ploughing depth was 20 cm (*reversible mounted plough Maschio Gaspardo S4); pre-sowing mineral fertilization over the entire fields (Amazone ZG-TS 8200 trailed spreader); high precision seeding after plough (seedbed cultivator Horsch Pronto 4DC).

Soil samples

After the fourth research year, following the winter wheat harvest, soil samples were collected from the experimental field. Soil was sampled from two depths, 0-30 cm (Ap horizon) and 30-50 cm deep (transitional EB horizon). 12 soil samples were taken with a spade along the transect of a plot for every replication. Then, a composite soil sample was prepared by mixing all subsamples from each plot (for each soil depth). This was done in four replications. For analysis, soil samples were air-dried, crushed and sieved using a 2 mm mesh sieve.

Analytical measurement methods

The particle size distribution of soil samples was determined using a laser diffraction particle size analyzer Mastersizer 2000 (Malvern Instrument, the UK). Soil pH was measured potentiometrically in 1M KCl solution (soil: solution ratio 1:2.5) using the pH-meter MultiCal pH 540 GLP WTW. Soil samples were mineralized in a mixture of HF and $HClO_4$ to determine the total metal content. The content of available metal forms was assayed using 0.005 mol L^{-1} diethylene triamine pentaacetic acid (DTPA) according to the Lindsay and Norvell method (1978) and ISO 14870 (2001). The method for extracting of heavy metals using a buffered DTPA solution has been widely and successfully applied in diagnosis of microelement deficiency in arable soils. This method mainly applies to testing the availability of copper, iron, manganese and zinc to plants which grow on the analyzed soils. In this study, concentrations of metals were determined with the atomic absorption spectrometry method on a Philips PU 9100 spectrometer (Cambridge, the UK). The content of total organic carbon (TOC) and content of total nitrogen (N_t) were assayed with a Vario Max CN analyser made by Elementar (Germany).

Statistical analysis

The analysis of variance (ANOVA) was used to evaluate the effects of a tillage system and depth of cultivation on the variables, and the least significant differences (*LSD*) were used to compare means ($P<0.05$). To evaluate the results, Statistica 10 software (StatSoft, Tulsa, USA) was applied. A cluster analysis was performed for the results by applying the Ward's method, which is based on the analysis of variance. This method involves an agglomerative clustering algorithm.

RESULTS AND DISCUSSION

A field experiment was set up on a Haplic Luvisol (IUSS Working Group WRB, 2015) with the grain size composition of sandy loam in the surface layer (Table 1). The soil samples in the topsoil prior to the field experiment included the total content of metals: Zn_t 38.0±0.8 mg kg^{-1}; Cu_t 6.2±0.3 mg kg^{-1}; Mn_t 310±4.6 mg kg^{-1} and Fe_t 14.9±0.7 g kg^{-1}. The mean content of TOC was 11.5 g kg^{-1} and pH_{KCl} – 6.10. The 30-50 cm layer was the only soil horizon in ST plots where silt loam was recorded, with 37.1% of sand, 57.1% of silt and 5.8% of clay. Soil texture and pH of the plots were similar, which was evidenced by low values of the coefficient of variation (CV). The content of the clay fraction was significantly higher in the subsurface layer. The illuvial deposits of the clay fraction accumulated in the subsoil horizon of the Haplic Luvisol classified as the transitional EB horizon. Up to the depth of 50 cm, the soil pH was slightly acidic. The total amounts of Zn_t, Cu_t, Mn_t and Fe_t (Table 2) were similar to the geochemical background concentrations and lower than the admissible content in arable soils of Poland (Zgłobicki et al. 2011, Kobierski, Dąbkowska-Naskręt 2012, Journal of Laws... 2016). A significantly higher mean total content of metals was recorded in the RT system.

Table 1

Soil characteristics due to tillage treatment

Tillage treatment	pH	Particle size composition (%)			Soil texture Class PTG (2009)
		sand	silt	clay	
	1 M KCl	(2-0.05 mm)	(0.05-0.002 mm)	(<0.002 mm)	
(FIT) 0-30 cm	6.01	50.0	44.7	5.3	SL
(RT) 0-30 cm	6.17	45.2	49.2	5.6	SL
(ST) 0-30 cm	6.19	47.8	46.7	5.5	SL
Mean	6.12	47.7	46.9	5.5	
SD	0.10	2.40	2.25	0.15	
CV (%)	1.6	5.0	4.8	2.7	
(FIT) 30-50 cm	6.16	45.4	48.4	6.2	SL
(RT) 30-50 cm	6.27	46.0	47.1	6.9	SL
(ST) 30-50 cm	6.07	37.1	57.1	5.8	SiL
Mean	6.17	42.8	50.9	6.3	
SD	0.10	4.97	5.43	0.56	
CV (%)	1.6	11.6	10.7	8.9	

SD – standard deviation, CV – coefficient of variation, FIT – full-inversion tillage, RT – reduced tillage, ST – strip-till, SL – sandy loam, SiL – silt loam, PTG – Polish Society of Soil Science

The FIT and ST treatments could have accelerated the leaching of heavy

Table 2

Total content of Zn_t, Cu_t, Mn_t, Fe_t and their form extracted with DTPA solution

Layer	(A) Tillage system			Mean	(A) Tillage system			Mean
	FIT	RT	ST		FIT	RT	ST	
	Zn_t (mg kg^{-1})				Zn_{DTPA} (mg kg^{-1})			
0-30 cm	37.7	40.3	37.0	38.3	2.83	2.47	2.72	2.67
30-50 cm	39.5	43.0	38.8	40.4	2.72	2.31	2.53	2.52
Mean	38.6	41.6	37.9		2.78	2.39	2.63	
$LSD_{(0.05)}$	A=1.87; B=1.16; B/A=n.s.; A/B=n.s.				A= 0. 07; B=0.10; B/A=0.17; A/B=0.17			
	Cu_t (mg kg^{-1})				Cu_{DTPA} (mg kg^{-1})			
0-30 cm	6.09	6.79	6.48	6.45	0.91	1.02	1.16	1.03
30-50 cm	6.41	7.58	7.05	7.01	0.82	1.05	0.99	0.96
Mean	6.25	7.18	6.76		0.86	1.03	1.07	
$LSD_{(0.05)}$	A=0.38; B= 0.18; B/A= n.s.; A/B=n.s.				A=0.10; B=0.03; B/A=0.07; A/B=0.11			
	Mn_t (mg kg^{-1})				Mn_{DPTA} (mg kg^{-1})			
0-30 cm	308	330	313	317	17.7	17.8	18.2	17.9
30-50 cm	319	348	317	328	14.4	12.9	16.4	14.6
Mean	313	339	315		16.0	15.3	17.3	
$LSD_{(0.05)}$	A=21.3; B= 10.1; B/A=n.s.; A/B=n.s.				A=1.71; B=1.41; B/A=n.s.; A/B=n.s.			
	Fe_t (g kg^{-1})				Fe_{DPTA} (mg kg^{-1})			
0-30 cm	14.2	15.3	14.7	14.7	24.8	25.7	24.0	24.9
30-50 cm	16.5	17.4	17.0	17.0	29.7	25.4	24.0	26.4
Mean	15.3	16.3	15.8		27.2	25.5	24.0	
$LSD_{(0.05)}$	A=0.40; B=0.62; B/A=n.s.; A/B=n.s.				A=0.78; B=1.42; B/A=2.45; A/B=2.28			

LSD – least significant difference, FIT – full-inversion tillage, RT – reduced tillage, ST – strip-till, n.s.– non-significant differences

metals down the soil profile. The results of the cluster analysis confirm the dependence of the total metal content and their available forms (Figure 2). The FIT and ST systems are grouped depending on the soil layer. After chemical weathering, metals are released and either redistributed on soil constituents or mobilized and leached deep down the soil profile (Lamy et al. 2006). In the subsurface layer, accumulation of metals occurred predominantly in pedofeatures (clay, iron coatings) related to characteristic soil processes in the illuvial horizon (van Oort et al. 2018). The relative accumulation of total heavy metals at the depth of 30-50 cm, when studied after the applied tillage technology, can be related to the clay fraction distribution in the soil. A different relationship was noted for the average content of Zn_{DTPA}, Cu_{DTPA}, Mn_{DTPA} since the soil in the surface layer contained a significantly higher content thereof. Soil organic matter plays a significant role in retaining trace elements, essential for plant growth. The retention mech-

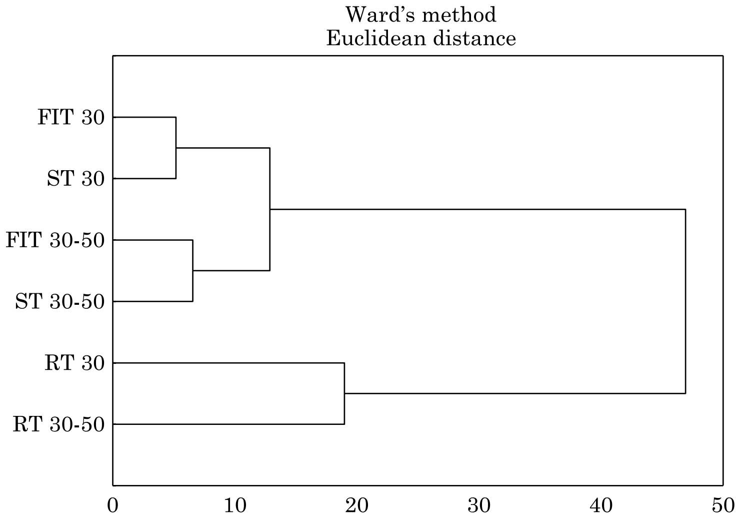

Fig. 2. Cluster analysis: total content of metals and their DTPA extractable forms, and the clay fraction

anisms of trace elements by organic matter involve mainly the formation of metal-organic complexes (KALEMBASA, PAKUŁA 2009). Soil cultivated in the FIT system contained a significantly higher content of Zn_{DTPA} and Fe_{DTPA} than soil under the RT and ST systems, whereas the FIT system significantly lowered the content of Cu_{DTPA} in soil. The content of metals extracted with the DTPA solution was considerably higher than the content considered deficient for plants (KARAMANOS et al. 2003).

As demonstrated in Table 3, the tillage method was one of the factors affecting the content of SOM, an observation also reported by POWLSON et al.

Table 3

Content of total organic carbon (TOC), total nitrogen (N_t)

Layer	(A) Tillage system			Mean	(A) Tillage system			Mean
	FIT	RT	ST		FIT	RT	ST	
	TOC (g kg^{-1})				N_t (g kg^{-1})			
0-30 cm	11.71	12.55	11.22	11.83	1.18	1.24	1.17	1.20
30-50 cm	9.00	9.42	7.15	8.52	0.96	0.96	0.72	0.88
Mean	10.35	10.98	9.19		1.07	1.10	0.95	
$LSD_{(0.05)}$	A=0.61; B=0.43; B/A=0.74; A/B=0.89				A=0.09; B=0.07; B/A=0.13; A/B=0.14			
	TOC/N_t							
0-30 cm	9.70	10.28	9.55	9.84				
30-50 cm	9.43	9.96	9.96	9.78				
Mean	9.56	10.12	9.75					

Description as given under Table 2.

(2012), Laufer et al. (2016) and Kassam et al. (2019). A significantly higher mean content of TOC and N_t was recorded for the RT as compared with the FIT and ST systems. As reported by Liaudanskiene et al. (2013), reduced soil tillage treatments increased the SOM content in the topsoil layer in a relatively short time and improved the soil quality. The content of TOC and N_t at the depth of 30-50 cm was significantly lower than in the 0-30 cm layer, which is connected with the inflow of organic matter. The content of TOC and N_t determined values of the TOC/N_t ratio. The availability of nitrogen and the SOM decomposition rate depend on the value of this ratio in microbiologically active soil. A high rate of SOM mineralization due to intensive treatments can intensify the release of dissolved organic carbon and increase the percentage of TOC (Andruschkewitsch et al. 2013). Halpern et al. (2010) stated that the labile carbon fractions are physically protected in aggregates under the RT system and suggested that measurements of labile fractions could be the best indicator of management-induced changes in the total SOC content. The values of the TOC/N_t ratio in the analyzed soils show that the tillage systems did not affect this parameter (Table 3). The average values of the TOC/N_t ratio ranged from 9.56 in soil cultivated in the FIT system to 10.12 in soil submitted to the RT system, which suggests that the soils showed a similar organic matter decomposition rate regardless of the cultivation method. A lower TOC/N_t ratio is in general associated with higher rates of SOM decomposition (Booth et al. 2005). Soil sampling below the tillage depth allows more accurate assessment of TOC and N_t content and evaluation of the impact of management practices on the chemical parameters (van Eerd et al. 2014). The Haplic Luvisol under study showed a significantly higher content of the clay fraction, which can play a SOM-protective function, at the 30-50 cm depth.

The results confirm that a tillage system is an important factor determining the distribution of heavy metals and the content of TOC in soils, although the pedogenic properties affecting the arable soil quality must be considered as well.

CONCLUSIONS

1. Tillage and seedbed preparation involved in the FIT and ST systems significantly decreased the total content of Zn_t, Cu_t, Mn_t and Fe_t in soils compared with the RT system. The soil cultivated in the FIT system had a significantly higher content of Zn_{DTPA} and Fe_{DTPA} than soil under the RT and ST systems. A significantly higher content of zinc, copper and manganese available for plants was found in the surface layer. These concentrations were higher than the deficiency threshold content for the proper development of plants.

2. The average values of the TOC/N_t ratio were similar, which indicates a similar decomposition rate of organic matter regardless of the tillage system. The highest TOC content was recorded in the soil sampled from the 0-30 cm layer of the plots cultivated under the RT system. The ST system did not affect the content and quality of SOM significantly, as compared with the RT and FIT systems.

3. The results of the cluster analysis confirm that the content of the heavy metals was mainly controlled by the FIT and ST systems, nevertheless the distribution of the clay fraction in the surface and the subsurface layer of soils is also essential.

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