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Effects of long-term tillage practices on the quality of soil under winter wheat

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ABSTRACT

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These studies were done in 2013–2016 on the effects of two tillage systems on the quality of a loamy sand soil (Eutric Fluvisol) and were based on a field experiment started in 2002. Winter wheat was grown in conventional tillage (CT) with mouldboard ploughing (inversion) tillage; and reduced (non-inversion) tillage (RT) based on soil crushing-loosening equipment and a rigid-tine cultivator. Chopped wheat straw was used as mulch in both treatments. The physical, chemical and biological properties of the soil were investigated. RT increased soil bulk density in the 0–5 cm and 5–10 cm depth layers in comparison with CT. The greatest content of soil organic carbon (SOC) was found in the 0–5 cm layer under RT. The BIOLOG EcoPlate System showed that soil under RT had a greater metabolic activity and diversity of microbial communities than soil under CT. RT improved the quality of the surface soil as shown by the greater content of SOC and microbial activity measured in terms of dehydrogenases. However, the mean yields of winter wheat under RT and CT were similar. This suggests that the effects of increased bulk density (BD) on yield can be compensated by the effects of the improved microbial status.

Keywords: soil quality; cultivation; microorganisms; microbial diversity; *Triticum aestivum* L.

Different frequency and intensity of tillage alter soil physical, chemical and microbiological properties that are all indicators of soil quality (SQ) (Doran et al. 1996). Enzymes, especially dehydrogenases (DH), have been used for many decades as indicators of SQ because of their role in nutrient cycling and decomposition (Doran et al. 1996, Mikanová et al. 2012, Wolińska et al. 2013). Soil organic carbon (SOC) is the most important indicator of SQ because of its impact on key soil properties. The soil bulk density (BD) is defined as the mass of solids per unit volume of moist soil. If BD becomes too high, it can limit plant root growth and yield production. For this reason, BD is often used as an indicator of SQ and included in many soil data sets. The value of BD that will adversely affect plant root growth and development depends on many factors including the crop being

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grown, and the management history (Nosalewicz and Nosalewicz 2011, Małecka et al. 2012). Several authors (Tebrügge and Düring 1999, Czyż and Dexter 2008) reported a significant increase in BD in no-tillage (NT) or reduced tillage (RT) in comparison with conventional tillage (CT) for the soil depths corresponding to the plough layer in CT. However, some authors observed no significant or systematic differences in BD between RT and CT (Ferreras et al. 2000, Anken et al. 2004). Under conditions of minimal vehicular traffic, BD is a function of natural factors (Carter 1990). Microbial diversity can be measured using various technique, e.g. the BIOLOG EcoPlate System. This allows testing for a number of ecologically-relevant substrates with replication, enables evaluation of the metabolic profile diversity of soil microorganisms, and allows quick determination of the ecological status of the microbial population in environmental samples (Frąc et al. 2012). Earlier studies showed that RT improves soil aeration, water infiltration, decreases SOC mineralization and therefore increases the size, diversity and activity of microbial communities. Such changes in SQ can affect plant growth and yield (Arvidsson et al. 2013, Małecka et al. 2015). This study was done to evaluate the effects of CT and RT on SQ by monitoring changes in some physical (BD), chemical (SOC content) and microbiological (activity of DH, microbial metabolic diversity) properties of a loamy sand soil and in the yield of winter wheat.

MATERIAL AND METHODS

Field trial. A long-term field experiment was established in 2002 at the Institute of Soil Science and Plant Cultivation State Research Institute experimental station in Grabów, Poland on a loamy sand soil (Eutric Fluvisol) with initial SOC content of 0.71% at 0–10 cm depth and 0.61% at 10–20 cm depth (Czyż and Dexter 2008). Winter wheat cv. Jantarka was grown in monoculture under conventional (inversion) tillage (CT) based on the mouldboard plough (to 25 cm depth) and traditional soil tillage equipment, and reduced (non-inversion) tillage (RT) based on soil crushing-loosening equipment and a rigid-tine cultivator (to 10 cm depth). Tillage was done at the water content at or close to 0.19–0.20 kg/kg soil. This is the optimum water content for tillage of this soil as calculated from the water retention curve (Dexter and Bird 2001). Chopped wheat straw was used as mulch on both treatments. Fertilizer was applied to both treatments as follows: fall-applied mineral fertilizer Polifoska 18 kg N/ha, 60 kg P/ha and 90 kg K/ha; spring-applied mineral N (NH_4NO_3) 150 kg N/ha in 3 doses – 70 kg N/ha – beginning of spring growth, 55 kg N/ha – stem elongation and 25 kg N/ha – heading. Winter wheat was grown according to fertilization and weed control recommendations used in Poland. The herbicide programme for tillage systems used pre-plant and post-emergence applications (Komplet 560 SC 0.5 L/ha – applied in mid-late October, Chwastox Turbo 340 SL 2 L/ha – applied in early April).

Soil samples. During years 2013–2016 soil samples were collected each year from the fields at harvest with 4 replications at 0–5, 5–10, 15–20 and 30–35 cm depths. Some soil characteristics are presented in Table 1. The weather conditions are shown in Table 2. Both mean air temperature and the sum of precipitation differed significantly between the years.

Physical properties. The soil particle size distribution was determined by the Casagrande aerometric method as modified by Prószyński (Litynski

Table 1. Basic soil characteristics at 0–20 cm depth under both tillage treatments for year 2013–2016

Treatment	pH_{KCl}	P	K	Mg	Particle size distributions (%)			Soil textural class
					total sand	silt	clay	
		(mg/kg soil)			(2–0.02 mm)	(0.02–0.002 mm)	(< 0.002 mm)	
CT	6.4	211	103	70	76.32	21.61	2.07	loamy sand
RT	6.0	164	91	88	76.05	21.89	2.06	loamy sand
$LSD_{0.05}$	ns	25	11	6	ns	ns	ns	–

CT – conventional tillage; RT – reduced tillage; *LSD* – least significant difference; ns – non significant

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Table 2. Monthly mean air temperature and total precipitation and long-term average (1976–2013) at Grabów experimental station (Poland)

Month	Temperature (°C)					Precipitation (mm)				
	1976/2013	2012/13	2013/14	2014/15	2015/16	1976/2013	2012/13	2013/14	2014/15	2015/16
IX	13.1	14.5	11.8	17.9	15.0	62.1	21.8	63.9	15.9	93.9
X	8.2	8.1	9.5	9.8	6.8	42.3	83.5	3.0	28.5	12.2
XI	3.1	5.3	5.2	4.7	5.0	40.5	29.4	48.0	25.7	38.7
XII	–0.9	–3.4	1.6	0.5	3.9	36.8	27.4	15.7	36.3	24.0
IX	–2.6	–3.6	–2.6	1.0	–3.6	32.2	45.4	46.6	40.3	32.1
II	–2.0	–1.1	1.4	0.5	3.4	26.5	37.5	25.1	15.1	64.1
III	2.0	–2.1	6.3	5.0	3.9	38.0	41.1	42.0	63.2	52.3
IV	8.2	8.3	9.9	8.1	9.2	44.0	29.9	56.6	34.8	45.1
V	13.8	15.3	13.5	12.7	14.9	63.6	112.0	124.9	107.0	39.4
VI	16.7	18.6	15.2	16.9	18.7	78.4	116.3	90.7	30.3	60.1
VII	18.6	19.7	20.4	19.7	19.2	89.7	20.8	115.3	51.7	81.9
VIII	17.9	19.2	17.9	22.1	18.1	77.6	11.6	98.8	6.2	53.6

et al. 1976). This enabled the content of clay (mineral particles < 2 µm) to be determined. Soil bulk density was measured using 100 mL cylinder samples of undisturbed soil by weighing before and after drying at 105°C for 48 h. The dry BD was calculated as the mass of dry soil per unit volume of moist soil.

Chemical properties. The SOC content was measured by wet oxidation using the Tiurin method. Soil pH_{KCl} was measured potentiometrically (1:2.5 mV) in water and in a 1 mol/L KCl solution, respectively (ISO 10390, 2005). Available P and K were determined by the Egner-Rhiem method and available Mg by the Schachtschabel method.

Microbiological activity. The activity of soil dehydrogenases was determined in moist soil using TTC (2,3,5-triphenyltetrazolium chloride) as a substrate (Casida et al. 1964).

Biolog EcoPlate method. Diversity of the catabolism in the soil microbial community was analysed using the EcoPlate method (Biolog Inc., Hayward, USA). Fresh soil (1 g) was suspended in 99 mL sterile water and shaken for 20 min. Next, the samples were incubated at 4°C for 30 min. After cooling, the soil solutions were filtered (Bag Filter, Interscience) and each of the 96 wells on the EcoPlate were inoculated with 120 µL of sample. Microplates were incubated at 25°C for 168 h. Measurements were made every 24 h in the MicroStation at 590 nm.

Statistical analysis. Statistical analysis of variance (ANOVA) was used to evaluate the effects of tillage on the measured variables, and the least significant differences (*LSD*) were used to compare means ($P < 0.05$). Pearson correlation coefficients were calculated to show the relations between soil properties and winter wheat grain yield (WWY) at $P < 0.01$ and $P < 0.05$.

RESULTS AND DISCUSSION

The BD of the top soil layer was different ($P < 0.05$) in the two tillage systems (Figure 1a). After 11–14 years of different tillage, the RT system had increased BD in the top layer, especially at 0–5 cm and 5–10 cm depths as compared with CT. At the 0–5 cm and 5–10 cm depths, RT caused BD increase in the surface soil of 0.20 and 0.21 g/cm^3, respectively, as compared with CT. The highest values of BD were found in the 30–35 cm layer, where no significant effect of tillage systems on BD was observed. Differences in BD between CT and RT systems were not significant at the 15–20 cm depth; however, BD in RT was slightly higher than in CT. The average values of BD at 0–20 cm under RT were higher (1.71 g/cm^3) than under CT (1.56 g/cm^3). The greatest values of BD occurred deeper (30–35 cm) for CT and RT (1.62 and

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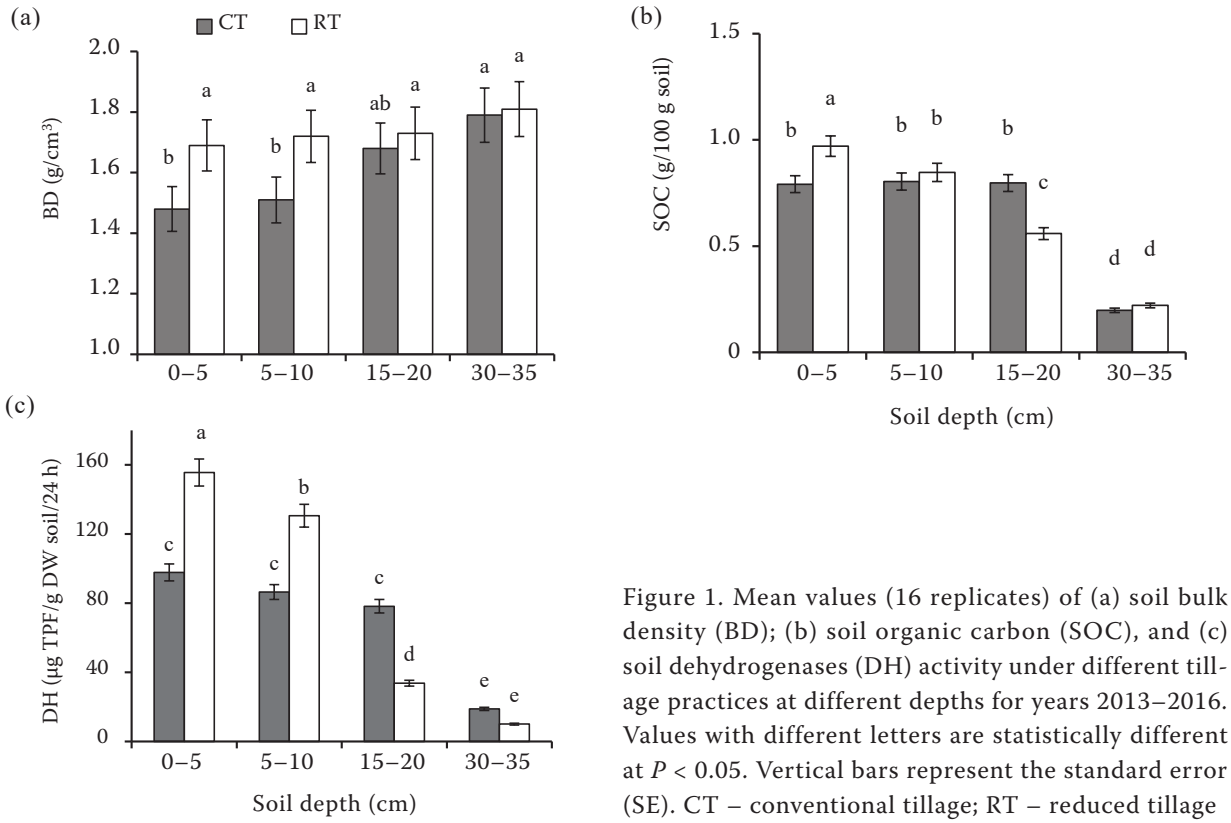

Figure 1. Mean values (16 replicates) of (a) soil bulk density (BD); (b) soil organic carbon (SOC), and (c) soil dehydrogenases (DH) activity under different tillage practices at different depths for years 2013–2016. Values with different letters are statistically different at $P < 0.05$. Vertical bars represent the standard error (SE). CT – conventional tillage; RT – reduced tillage

1.74 g/cm^3, respectively) as compared with BD at 0–20 cm. This may be due to a tillage pan that had been formed before the experiment began. An earlier research of Czyż and Dexter (2008) showed that less intense tillage resulted in significant changes in BD, water content and soil stability. Similarly, Mühlbachová et al. (2015) in a long-term field experiment on an Orthic Luvisol with clay loamy texture in the Prague-Ruzyně region (Czech Republic) found greater BD values in the 0–10, 10–20 and 20–30 cm layers of NT than in CT. Małecka et al. (2012) also found a significant difference in BD of a loamy sand (Albic Luvisols) at the 0–5 cm depth. After 7 years of cultivation RT and NT caused an increase of BD in the top soil of 0.15 and 0.30 g/cm^3, respectively as compared with CT. Differences in BD between tillage systems were not significant at the 10–20 cm depth; however, BD in CT was slightly smaller than in RT and NT.

The SOC content at different depths under CT and RT is shown in Figure 1b. The highest SOC content 0.97 g/100 g soil was in the top layer at the 0–5 cm depths under RT. The results show that the RT treatment significantly increased the SOC content by 23% mostly in the 0–5 cm soil layer as compared with CT (0.79 g/100 g soil). Mühlbachová et al. (2015) in a long-term field experiment also showed that RT and NT increased the SOC contents in top layers of soil. Similarly, Franzluebbers (2002) reported that the main differences between CT and NT are in the top few centimetres of soil.

The highest activity of soil DH was in the 0–5 cm and 5–10 cm depths under RT at 155.6 and 130.6 µg TPF g/DW (dry weight) soil/24 h, respectively (Figure 1c). At these depths, the soil DH activity was higher by 57.8 and 44.1 µg TPF g/DW soil/24 h, respectively, as compared with CT; this result is consistent with Doran et al. (1996) and Wolińska et al. (2013). At the 15–20 cm and 20–30 cm depths, the average activity of DH was smaller under RT than under CT. In sub-arable soil layer (30–35 cm) the DH activity was the lowest under both RT and CT at 18.9 and 10.0 µg TPF g/DW soil/24 h, respectively. RT stimulated the activity of soil microbial communities as shown by the greater DH activity in comparison with CT. This stimulation of soil DH is of importance in processes of nutrient liberation for plants. Comparable results were obtained by Mikanová et al. (2009) and Gajda et al. (2013).

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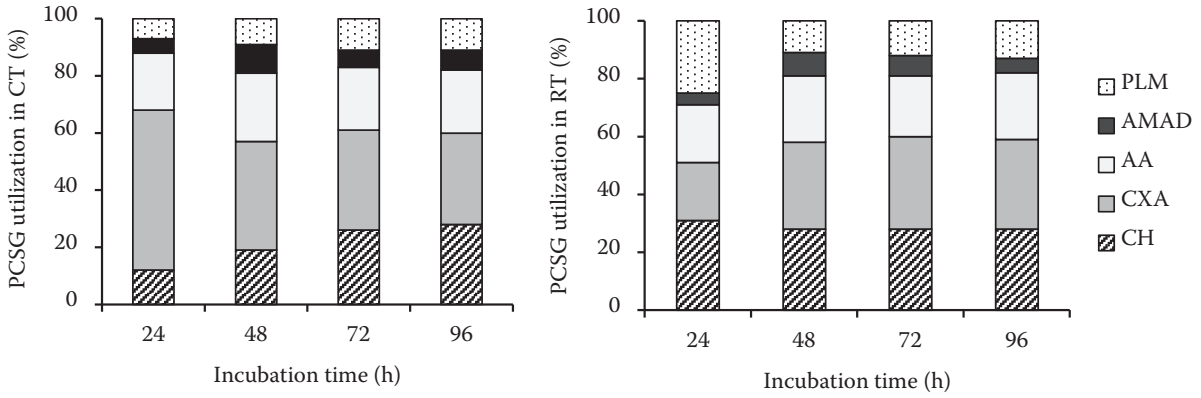

Figure 2. Percentage of utilization of particular carbon substrates group (PCSG) by microbial communities influenced by different tillage practices within 96 h of incubation. PLM – polymers; AMAD – amines and amides; AA – amino acids; CXA – carboxylic acids; CH – carbohydrates; CT – conventional tillage; RT – reduced tillage

The analysis of the metabolism of microorganisms has revealed that the microbial community metabolized all groups of substrates (Figure 2). Greater metabolic diversity was observed in RT than in CT. The different abilities of soil microorganisms to metabolize 31 offered sole C sources [8 carbohydrates (CH), 8 carboxylic acids (CXA), 4 polymers (PLM), 6 amino acids (AA), 3 miscellaneous substrates and 2 amines and amides (AMAD) – all 3-times replicated on each microplate] were demonstrated. Soil microorganisms in CT and RT most intensively catabolized substrates from the group of CXA, and the least those from the group AMAD. For both soils, the percentage utilization of different groups of carbon substrates is presented for 24–96 h of total incubation time, in which differentiation in microbial metabolic activity is the most visible.

After 24 h, the soil microbial community in RT metabolized the CH, PLM, CXA, AA and AMAD groups up to 31, 25, 20, 20, and 4%, respectively, whereas the microbial community in CT metabolized substrates differently. In CT the CH and PLM group utilization rate was slower and reached up to 12% and 7%, respectively, but only the rate of CXA group utilization reached up to 56% at the same time and was greater than in RT soil. The AA, and AMAD groups were utilized similarly as in RT soil (20% and 4–5%, respectively), but the utilization rate of PLM group was slower and reached 7%, on average, compared to RT soil.

After 48 h the metabolic activity of soil microbial populations changed in both tillage systems. After 48 h in RT, an increase in utilization rate of CXA and AMAD groups to 30% and 8% was found, respectively, while the utilization rate of PLM group declined to 11% compared to the catabolic rates observed after 24 h. In CT, an 18% decrease, on average, in the rate of CXA group utilization was observed but the rates of CH, AA, AMAD, and PLM groups increased by 7, 4, 5 and 2%, respectively, in relation to 24 h.

After 72 h, the metabolic activity of microorganisms had not changed significantly in RT compared with 48 h. In CT, microbial metabolic activity increased, especially in utilization of CH and PLM groups up to 26% and 11%, respectively. For the next 24 h of incubation, catabolic activity of microorganisms in soil under both treatments became more stable and the readings at 96 h did not show any significant changes in the rate of

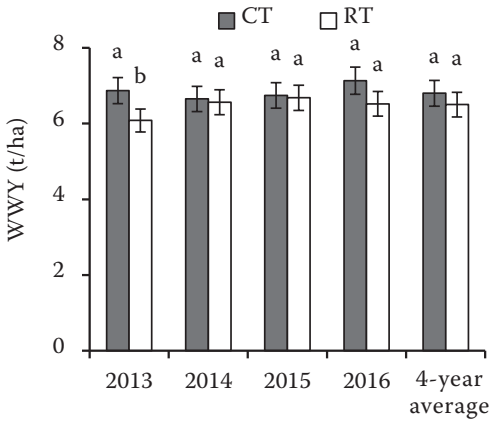

Figure 3. Mean values (16 replicates) of grain yields of winter wheat under different tillage practices for years 2013–2016. Values with different letters are statistically different at the $P < 0.05$. Vertical bars represent the standard error. WWY – winter wheat grain yield; CT – conventional tillage; RT – reduced tillage

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Table 3. The correlation coefficients obtained between selected soil properties, precipitation and winter wheat grain yields

Related parameter		Correlation coefficient	Level of significance
DH	PCSG	0.683**	high degree positive
	SOC	0.906**	high degree positive
	BD	–0.410*	significant negative
	PCP	0.464*	significant positive
PCSG	SOC	0.720**	high degree positive
	BD	–0.476*	significant negative
WWY	DH	0.377*	significant positive
	PCSG	0.242	non significant
	SOC	0.162	non significant
	BD	–0.426*	significant negative
	PCP	0.435*	significant positive

DH – dehydrogenases activity; PCSG – particular carbon substrates group utilized by microbial communities; SOC – soil organic carbon; BD – bulk density; WWY – winter wheat grain yields; PCP – precipitation; $^{**}P < 0.01$; $^{*}P < 0.05$

utilization of 5 groups of carbon source on incubated EcoPlates. Also, Yang et al. (2013) observed significantly higher utilization rates of AA, CH, and PLM groups up to 68, 67 and 23%, respectively under NT than under CT ($P < 0.01$). Furthermore, Habig and Swanepoel (2015) reported markedly higher metabolic diversity in RT than in CT. This was attributed to the higher disruption in microbial development, metabolic activity and abundance due to ploughing.

Tillage affects crop yield mostly through modifying soil BD, SOC, plant residues, and the diversity and activity of microbial communities (Małecka et al. 2015). In this study, the 4-year mean WWY under RT was 0.3 t/ha less (4.5%) than under CT, but this difference was not statistically significant (Figure 3). Arvidsson et al. (2013) reported similar results and suggested that an increase in BD reduced soil aeration, root growth and crop development, which might reduce crop yield under RT. However, higher microbial activity and favourable weather conditions such as temperature (2014–2016) and precipitation (2013–2015), particularly in May as compared with the long-term average (Table 2), may contribute to higher microbial activity and nutrient liberation for plants and mitigate the decrease of WWY caused by BD increase in RT relative to CT. These correlations demonstrate the high sensitivity of the studied parameters to changes in soil and show that SOC is the key for the activity and diversity of microbial communities (Table 3). The WWY showed correlations with PCP (0.435*), BD (–0.426*) and DH (0.377*) at $P < 0.05$.

In conclusion, the study have shown that soil under long-term cultivation of winter wheat with RT resulted in greater values of SOC, enzymatic activity, and greater microbial diversity and SQ than with CT, especially in the top (0–5 cm) layer. The EcoPlate System showed that soil under RT had a greater metabolic activity and diversity of microbial communities than under CT. However, RT increased soil BD, especially in the 0–5 cm and 5–10 cm depth layers in comparison with CT. These results suggest that the effects of increased BD on yield, as discussed in the introduction, can be compensated by the effects of the improved microbial status.

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