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The effect of various long-term tillage systems on soil properties and spring barley yield

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Abstract: This study, performed on a soil that is classified as Albic Luvisols that developed on loamy sands overlying loamy material (1.4% organic matter and pH 6.5), concerns the impact of tillage systems on soil properties and the yield of spring barley. The experiment design included 3 tillage systems: conventional tillage, reduced tillage, and no-tillage. Continuous cultivation for 7 consecutive years by reduced tillage and no-tillage led to changes in the physical properties of the surface soil layer (0-5 cm). At the stem elongation growth stage of spring barley, conservation tillage systems resulted in a higher water content and bulk density in relation to conventional tillage. Conservation soil tillage resulted in decreased penetration resistance in the 0-10 cm layer, as compared with conventional tillage. Reduced tillage and no-tillage favored the surface accumulation of organic C and total N in the soil, as well as that of available K and Mg. Our results suggest that conservation tillage systems lead to progressive improvement in soil nutrient status, but have little or no effect on crop yield. Only the no-tillage system had a negative effect on yield of spring barley, by 6.8% in comparison with conventional tillage.

Key words: Tillage systems, physical and chemical soil properties, spring barley yield

Introduction

Conservation agriculture is now widely recognized as a viable concept for sustainable agriculture due to its comprehensive benefits in economic, environmental, and social sustainability. The basic elements of conservation agriculture are: very little or no soil disturbance, direct drilling into previously untilled soil, crop rotation, and permanent soil cover (Holland 2004; Derpsch 2007).

Current tillage systems within Poland can be divided into 2 broad categories: inversion tillage, known as conventional tillage, and noninversion tillage, known more widely as conservation tillage with shallow cultivation or direct drilling. Conservation tillage has numerous positive effects on soil, such as improvement of water content (Husnjak et al. 2002; Boydaş and Turgut 2007) and reduction of soil erosion (Holland 2004; Morris et al. 2010). However, noninversion tillage can also lead to soil compaction, which could affect seed germination, root growth, and crop yield (D'Haene et al. 2008). The most common variables used to assess soil compaction in tillage studies are bulk density and penetration resistance. In several studies comparing tillage systems, greater bulk density and penetration resistance were found under reduced tillage and direct drilling, especially in the upper layer, than under conventional tillage (Özpinar and Çay 2005; McVay et al. 2006; Blecharczyk et al. 2007; Boydaş and Turgut 2007; Thomas et al. 2007).

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Changes in soil condition due to surface residue accumulation in continuous conservation tillage are substantial and characterized by increased soil organic matter (Blecharczyk et al. 2007; Fernández et al. 2007; Martin-Rueda et al. 2007; Thomas et al. 2007; López-Fando and Pardo 2009). The progressive increase in organic matter content in the first few centimeters of the soil profile increases the availability of the main nutrients (Fernández et al. 2007; Martin-Rueda et al. 2007; López-Fando and Pardo 2009), which are released to the rhizosphere at a faster rate than in conventional tillage (Fernández et al. 2007). Moreover, slower decomposition of surface-placed residues may prevent rapid leaching of nutrients through the soil profile, which is more likely when residues are incorporated into the soil.

Physical and chemical processes continually interact with time, resulting in a diversely arranged mixture of soil minerals, organic matter, and pore spaces that together define soil structure (Blanco-Canqui et al. 2005). Derpsch (2007) indicated that positive changes in soil properties are difficult to detect after only 2 or 3 years.

It is difficult to estimate the consequences of changes in soil quality on seed emergence and the growing conditions of plants. Changes in the same property can have different effects for crop growth and yield (Małecka et al. 2004; Angas et al. 2006; Machado et al. 2007; Martin-Rueda et al. 2007; Lepiarczyk and Stępnik 2009; Jug et al. 2011), depending on dominant soil and climatic conditions.

The objective of this experiment was to determine the effects of long-term tillage system combinations on some physical and chemical properties of soil and the crop yield of spring barley.

Materials and methods

The studies, carried out over the years 2003-2006, involved a static field experiment initiated in 1999 at the Brody Research Station of the Poznan University of Life Science, Poland (52°26′N, 16°17′E) on a soil classified as Albic Luvisols developed on loamy sands overlying loamy material (12% clay, 19% silt, and 69% sand). The 0-20 cm soil layer had 1.4% organic matter; a pH of 6.5 (measured in 1 M KCl); available P, K, and Mg concentrations of 207, 119 and 32 mg kg^{-1}, respectively; and a bulk density of 1.41 Mg m^{-3} at the beginning of the experiment. Prior to the start of this experiment, only plowing tillage had been applied for crops (mainly cereals) and the straw of cereals had been removed.

A spring barley cultivar, Atol, was grown in a 4-year rotation of peas, winter wheat, spring barley, and winter triticale. The sowing rate was 400 seeds m^{-2} for all tillage sown. The 3 tillage systems were arranged in a randomized block design in 4 replications, resulting in a total of 12 plots. The size of each tillage plot was 30 m in length and 5 m in width. The plots were separated by buffer strips of 0.3 m and there was a 6-m gap between the blocks for the tractor. The straw of the previous crop (winter wheat) was removed from all plots in all years.

The following tillage systems were applied in continuation: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). The CT consisted of tilling with a disk harrow (2.5 m wide) to a depth of 8 cm after the harvest of the previous crop, autumn plowing to a depth of 25 cm with a 3-furrow reversible plow (in the fourth week of October), and presowing tillage for seedbed preparation with a field cultivator followed by harrowing and rolling to a depth of 8 cm in the spring (1 week before sowing). The RT was done in the autumn (the fourth week of October) with only a stubble cultivator (2.5 m wide). The NT involved sowing directly into the stubble of the previous crop. The CT plots were drilled with a traditional grain drill (Poznaniak L, 2.5 m wide, row distance of 15 cm), and the RT and NT plots were drilled with a double disk drill (Great Plains, Solid Stand 10' equipped with a fluted coulter for residue cutting, a double disk for seed placement, and a single press wheel, 3.05 m wide, row distance 17.8 cm). A Zetor Forterra 10641 tractor was used for all tillage systems and sowing. The operating speed used for plowing and drilling was 1.5 m s^{-1}, and 1.8 m s^{-1} was used for other tillage treatments (cultivator and disk harrow). Speed was measured using a stopwatch and engine tachometer. Sowing dates were dependent on soil water conditions and occurred between March 25 and April 5, and the sowing depth for all tillage systems was 3-4 cm.

Fertilization was uniform for all tillage systems and each experimental year (90 kg N ha^{-1}, 35 kg P ha^{-1}, and 66 kg K ha^{-1}). The herbicide program for the tillage systems used preplant and postemergence applications. Before planting, 3 L ha^{-1} of glyphosate herbicide was applied on all plots with no-tillage and reduced tillage to control perennial weeds and volunteers. For weed control during the postemergence growing season, Stork 50 WG herbicide (thifensulfuron-methyl + carfentrazone-ethyl) was applied at the rate of 0.06 kg ha^{-1}. The seeds were dressed with Raxil Extra 060 FS fungicide (0.06 L 100 kg seeds^{-1}) containing thiuram and tebuconazole. For disease control, Folicur Plus 375 EC fungicide (tebuconazole + triadimenol) at the rate of 1.2 L ha^{-1} was applied to all plots at the GS 31 growth stage (Zadoks et al. 1974).

Measurements of penetration resistance (MPa), bulk density (Mg m^{-3}), and volumetric water content (%) of the soil were taken at the stem elongation growth stage (GS 31) of spring barley. Penetration resistance was measured for the depths of 0-10 cm, 10-20 cm, and 20-30 cm with a total of 16 replications for each tillage treatment and year. A hand-pushed penetrometer (Eijkelkamp Agrisearch Equipment, Model 06.01 Eijkelkamp, Giesbeck, the Netherlands) was used for the measurements with a cone diameter of 11.28 mm (cone number 1) in RT and NT and with a cone diameter of 15.96 mm (cone number 2) in CT. The area of the cone base was 1 cm^2 for cone number 1 and 2 cm^2 for cone number 2, and the tip angle was 30°. Soil bulk density was determined by the core method (Blake and Hartge 1986) at depths of 0-5 cm and 10-20 cm using 100 cm^3 cores (in 16 replications for each depth, tillage treatment, and year). The same cores were used to determine volumetric water content in the soil. Soil samples for chemical analyses were collected after the harvest of spring barley in 2006. The replication plot was represented by a mean sample consisting of 10 individual samples collected using an Egner sampler from the 0-5 cm and the 10-20 cm layer. After drying, the soil was crushed by hand and sieved through a 2-mm sieve. Organic carbon was determined using the Tiurin oxidation method, total N using the Kjeldahl method, available forms of P and K using the Egner-Riehm method, and available Mg using the Schachtschabel method (Page et al. 1982). Barley was harvested annually in early August from a 20 m^2 area using a 1.5-m wide Wintersteiger Classic Plot Combine. Grain yield was recalculated on standardized 15% grain moisture weight for t ha^{-1}. The following quality parameters of the spring barley were assessed: plant density per square meter at the beginning of tillering (4 frames with dimensions of 0.25 m^2 in growth stage GS 21), number of ears per square meter before harvest (4 frames with dimensions of 0.25 m^2 in growth stage GS 75), number of grains per ear (some 50 plants), and 1000-grain weight in grams (grains collected from the harvested grain mass; 2 × 500 grains were counted and weighed).

The results were tested using standard variance analysis (ANOVA) for the randomized complete block. Mean separations were made for significant effects with LSD and Tukey tests at probabilities of $P < 0.05$ and $P < 0.01$.

Results

The mean air temperatures during the vegetation period of spring barley (March-July) were higher than the 40-year mean, except in July 2004, March and May 2005, and March 2006 (Table 1). Growing season precipitation (March-July) in 2003, 2004, and 2006 was lower in comparison to the 40-year mean, except in 2005. Precipitation in 2003, 2004, and 2006 reached 70%, 75%, and 52% of the long-term mean value, but total precipitation during the season of March-June 2003 was lower than the 40-year mean. In 2005, the total precipitation was marginally higher, but precipitation shortages occurred in March, April, and June. Thus, weather conditions for the development of spring barley were the least favorable in 2006 and less favorable in 2003 than in the other years.

Physical properties of soil

It was found that tillage systems significantly affected the physical properties of the soil (Table 2). There was a significant difference in the soil water content with RT or NT in comparison to CT at both depth measurements. The soils tilled under RT and NT had higher recorded water content values, especially in the top layer. Volumetric water content values in the 0-5 cm soil layer increased by 3.1% under RT and 5.4% under NT relative to CT ($P < 0.01$). Water

Table 1. Mean daily air temperatures and total precipitation in the vegetation period of spring barley in 2003-2006 and 1961-2002 (from the Agrometeorological Observatory in Brody).

Years	Vegetation period					Mean or total
	March	April	May	June	July	
			Mean temperatures (°C)			
2003	3.5	8.2	16.0	19.8	19.6	13.4
2004	5.1	10.0	13.6	16.3	17.3	12.5
2005	1.8	8.8	12.8	16.4	19.7	11.9
2006	0.5	8.7	13.7	19.9	24.4	13.4
1961-2002	2.7	7.6	13.0	16.2	17.8	11.5
			Total precipitation (mm)			
2003	19.9	21.1	20.1	35.0	96.7	192.8
2004	20.9	23.3	44.3	58.8	59.6	206.9
2005	22.9	19.2	86.2	39.8	126.5	294.6
2006	36.8	47.2	41.4	7.7	9.9	143.0
1961-2002	38.2	38.5	55.2	66.4	77.1	275.4

Table 2. Volumetric water content and soil bulk density as affected by tillage system (mean of 2004-2006).

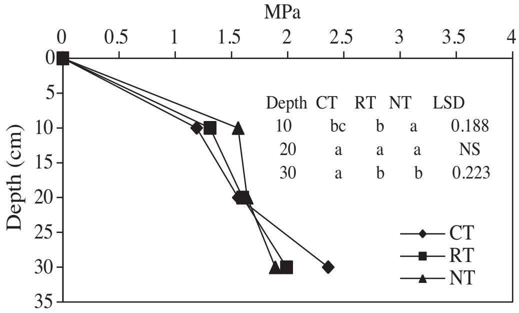
Tillage systems[a]	Volumetric water content (%)		Bulk density (Mg m^{-3})	
	Soil layer (cm)			
	0-5	10-20	0-5	10-20
CT	12.2 c	16.4 b	1.39 c	1.59
RT	15.3 b	18.0 a	1.54 b	1.62
NT	17.6 a	18.9 a	1.69 a	1.64
	LSD values			
Tillage systems	1.61**	1.32**	0.075**	NS

The means in a column with the same letter are not significantly different.
NS: not significant; **$P < 0.01$.
[a] Tillage systems: CT, conventional tillage; RT, reduced tillage; NT, no-tillage.

content values in the 10-20 cm soil layer increased by only 1.6% under RT and 2.5% under NT relative to CT ($P < 0.05$). In the 10-20 cm soil layer, the difference in soil water content between RT and NT was not significant.

The soil tillage systems significantly modified soil bulk density in the spring vegetation period of spring barley only in the upper soil layer ($P < 0.01$) (Table 2). At the 0-5 cm depth, RT caused an increase in the soil bulk density value in the surface soil layer of 0.15 Mg m^{-3}, and NT caused an increase of 0.30 Mg m^{-3} as compared with CT. Differences in bulk density between tillage systems were not significant at the 10-20 cm depth; however, bulk density in CT was slightly lower than in RT and NT.

Penetration resistance depends on the tillage system and its depth (Figure). Penetration resistance showed an increasing trend with depth for all treatments. During the growing period, there were statistically significant differences between the tillage systems in penetration resistance at the 0-10 cm depth ($P < 0.01$). The highest penetration resistance was obtained in NT (1.56 MPa), and the lowest in CT (1.19 MPa). On the other hand, in the 10-20 cm layer, the applied soil tillage systems did not result in significantly different soil penetration resistance. At the 20-30 cm depth, the opposite result was recorded because the determined parameter was significantly higher in CT (2.36 MPa) than in RT (1.99 MPa) and in NT (1.89 MPa), which may be a result of the development of a plow pan in CT ($P < 0.01$). Differences in the penetration resistance of the layers at 20-30 cm were not significant between RT and NT.



Depth	CT	RT	NT	LSD
10	bc	b	a	0.188
20	a	a	a	NS
30	a	b	b	0.223

NS: not significant; $P < 0.05$

Figure. Penetration resistance as affected by tillage system: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) (means of 2004-2006). NS: not significant; $P < 0.05$. The means in a row with the same letter are not significantly different.

Chemical properties

Conservation tillage systems lead to changes in nutrient distribution in the soil layer (Table 3). One of the effects produced by the different tillage systems after 7 years was the accumulation of organic C and total N at the soil surface under RT and NT. The concentration of organic C in RT, and particularly in NT, had increased significantly in the top layer (0-5

Table 3. Organic C, total N, and available forms of P, K, and Mg concentrations in the soil at the end of 7 years under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT).

Component	Soil depth (cm)	Tillage systems			LSD values
		CT	RT	NT	
Organic C $(g\ kg^{-1})$	0-5	8.07 b	9.55 a	10.18 a	0.63**
	10-20	7.97 a	7.60 ab	7.43 b	0.52*
Total N $(g\ kg^{-1})$	0-5	0.96 b	1.06 a	1.12 a	0.09**
	10-20	0.94	0.92	0.88	NS
C/N	0-5	8.4 b	9.0 a	9.1 a	0.04*
	10-20	8.5	8.3	8.4	NS
P $(mg\ kg^{-1})$	0-5	209	196	192	NS
	10-20	206	210	215	NS
K $(mg\ kg^{-1})$	0-5	149 c	204 b	225 a	19.3**
	10-20	142 a	126 b	120 b	11.2*
Mg $(mg\ kg^{-1})$	0-5	30.9 c	37.0 b	42.5 a	4.46**
	10-20	31.7 a	24.5 b	22.6 b	2.13*

The means in a row with the same letter are not significantly different.
NS: not significant; $^*P < 0.05$ and $^{**}P < 0.01$.

cm), by 18.3% and 26.1%, respectively, in comparison with CT ($P < 0.01$). Stocks of organic C in the 10-20 cm depth, in contrast, were significantly lower in NT plots than in the plots under CT practices. Differences between N stocks under tillage systems in the surface layer (0-5 cm) closely followed the pattern observed for organic C. Total N concentrations in RT and NT were greater by 10.4% and 16.7%, respectively, than under CT, but no significant differences between tillage systems appeared at the 10-20 cm interval. Measurements showed no significant differences in concentration of total N between RT and NT at the 0-5 cm intervals. The highest C-to-N ratio was obtained at the top soil layer (0-5 cm) of the NT plots, but no significant difference was observed between NT and RT. The difference in soil C-to-N ratios between tillage systems was not significant at the 10-20 cm depth.

Concentrations of available K and Mg were greater in the soil surface layer (0-5 cm) under RT by 36.9% and 19.7%, respectively, and under NT by 51.0% and 37.5%, respectively, than under CT (Table 3). The situation was reversed in a deeper layer (10-20 cm), where available K and Mg were greater in CT. There were no significant effects of tillage practices on available P in the 0-5 cm and 10-20 cm layers.

Grain yield and yield components

The yield of spring barley was closely related to the course of weather conditions, and especially to the total amount of precipitation in the vegetation period (Table 4). As for the tillage systems, on average, a greater grain yield was obtained in the years 2004 (6.00 t ha^{-1}) and 2005 (5.94 t ha^{-1}), with the most favorable weather conditions, while the lowest barley grain yield was in 2006 (4.84 t ha^{-1}), when the lowest amount of precipitation was associated with high temperatures. Spring barley had a significant negative reaction to only NT in all experimental years, although in 2005 the decreased yield was not statistically confirmed. In our investigation, the decrease of spring barley yield in NT was greater in 2004 (by 11.0%) and in 2006 (by 8.3%) than in 2003 (by 5.8%) and 2005 (by 0.5%) when compared with CT. On average, in the period of the experiment, the yield of spring barley in NT was significantly lower (by 6.4%) relative to CT ($P < 0.01$). The yield of spring barley in RT and CT ranged over a similar level, with the exception of the year 2003, when the yield in RT was significantly lower (by 7.3%) than in CT. In 2005, all tillage systems resulted in approximately the same values.

The decreased yield in NT resulted primarily from a lower plant population in the tillering phase, and, in consequence, from a lower number of ears per unit area. In NT, the mean number of ears per square meter was smaller by 7.3% than in CT. In RT, spring barley was characterized by a significantly lower number of ears per square meter (by 6.8%) in comparison with CT only in the first year of the studies. As to the 4-year average and all of the years combined, the number of grains per ear for all applied tillage systems had approximately the same values. However, spring barley grain in NT was characterized by a higher mass of 1000 grains than under RT and CT. On average, for the years of the studies, the 1000-grain weight of spring barley was significantly greater by 3.5% under NT in comparison with CT, and by 2.4% relative to RT, which was partially compensated for by a lower number of ears per square meter.

Discussion

After 4-7 years of experiments with different tillage systems for spring barley in Poland, the Brody Research Station found higher water content in the topsoil (0-5 cm) and in the lower part of the topsoil (10-20 cm) after RT and NT than after CT. Husnjak et al. (2002) and Boydaş and Turgut (2007) reported similar results. Stubble residues on the soil surface reduced evaporation. A lower volume of macropores and a higher volume of medium-sized water-holding pores are also possible reasons for higher water content in the soil after the use of conservation tillage systems. Soil water content is a highly variable parameter that depends on the dominant climatic and soil conditions. Generally, in years with high precipitation, no greater differences in soil water content are observed between CT and RT or NT, but in dry years, greater water content is found after NT (McVay et al. 2006).

Table 2 shows the effect of different tillage systems on soil bulk density. There was a significant difference in the soil bulk density with RT and NT compared to CT in the topsoil layer (0-5 cm). Similar results

Table 4. The effect of tillage system on spring barley grain yield and yield components.

Tillage systems[a]	Years				Mean
	2003	2004	2005	2006	
			Grain yield (t ha^{-1})		
CT	5.89 a	6.28 a	5.91	4.95 a	5.76 a
RT	5.46 b	6.12 a	6.09	5.02 a	5.67 a
NT	5.55 b	5.59 b	5.88	4.54 b	5.39 b
Mean	5.63	6.00	5.96	4.84	-
LSD values	0.234*	0.323**	NS	0.282*	0.231*
			Plant population after planting per square meter		
CT	340 a	350 a	330	337 a	339 a
RT	307 b	341 a	334	332 a	329 a
NT	311 b	303 b	321	309 b	311 b
Mean	321	331	328	326	-
LSD values	12.3*	24.9**	NS	19.9	17.7*
			Number of ears per square meter		
CT	514 a	539 a	521	509 a	521 a
RT	479 b	520 a	529	501 a	507 ab
NT	484 b	485 b	513	449 b	483 b
Mean	492	515	521	486	-
LSD values	22.5*	34.6**	NS	30.4**	29.8*
			Grain number per ear		
CT	22.4	22.8	23.3	21.8	22.6
RT	22.1	22.9	22.8	22.7	22.6
NT	21.7	22.1	22.1	22.1	22.0
Mean	22.1	22.6	22.7	22.2	-
LSD values	NS	NS	NS	NS	NS
			1000-grain weight (g)		
CT	51.1 b	51.0 b	48.7 b	44.6 b	48.9 b
RT	51.6 b	51.4 ab	50.5 a	44.1 b	49.4 b
NT	52.8 a	52.3 a	51.3 a	45.8 a	50.6 a
Mean	51.8	51.6	50.2	44.8	-
LSD values	1.01*	1.28*	1.26*	1.09*	1.01*

The means in a column with the same letter are not significantly different.
NS: not significant; *P < 0.05 and **P < 0.01.
[a]Tillage systems: CT, conventional tillage; RT, reduced tillage; NT, no-tillage.

for soil bulk density were reported by McVay et al. (2006), Blecharczyk et al. (2007), and Thomas et al. (2007). Moreover, research results obtained in long-term experiments with NT indicate a decrease in the bulk density of the upper soil layer in comparison with the conventional tillage system. This would be related to the existing stubble residue on top of nontilled soils that provides organic matter and food for soil fauna, particularly for earthworms, which loosen surface soil through burrowing activities (Katsvairo et al. 2002; Blanco-Canqui et al. 2005). A high soil bulk density reduces aeration and increases penetration resistance, limiting root growth and development of crops (D'Haene et al. 2008). In our experiment, penetration resistance was higher under RT and NT than CT at the surface. The lack of change in penetration resistance with increasing soil depth under RT and NT contrasted with lower resistance under CT in the upper soil layer. Penetration resistance values for all treatments in the 0-20 cm layer were below the critical 2-3 MPa level. Values above this level are generally considered slow for root growth (Bengough and Mullins 1990). At a 20-30 cm depth, where the tractor wheels compact the soil during plowing, compaction of the soil was less under RT and NT. The effects of tillage systems on soil penetration resistance are highly variable. For example, soils under CT may have lower (Özpinar and Çay 2005; Blecharczyk et al. 2007; Boydaş and Turgut 2007), equal (Katsvairo et al. 2002), or higher (Blanco-Canqui et al. 2005) penetration resistance than those under NT or RT. It depends on the soil and the time since the last tillage operation.

Several studies have indicated that the introduction of no-tillage systems leads to improved soil nutrient recycling, especially with respect to increased organic C closer to the soil surface (Blanco-Canqui et al. 2005; Özpinar and Çay 2005; McVay et al. 2006; Blecharczyk et al. 2007; Pereira et. al. 2007; Thomas et al. 2007; López-Fando and Pardo 2009; Lenart and Sławiński 2010). In general, our results are in agreement with those obtained by the studies above. A total of 7 years of tillage resulted in higher organic C, total N, available K, and Mg content under RT and NT than under CT in the 0-5 cm soil layer. Urbanek and Horn (2006) suggested that, in conservation tillage, the accessibility of organic C for microorganisms and for leaching into deeper horizons of soil is reduced, and less organic C is removed from the soil than in conventional tillage. The increase in the organic C content under RT and NT may contribute to greater aggregate stability and lower sensitivity to erosion by water (McVay et al. 2006). Many such soil modifications start 4-5 years after the beginning of the conservation tillage systems. Continuous, long-term plow-free management can sustain or even improve soil quality (Derpsch 2007). According to Derpsch, after many years of using a conservation tillage system, it may be possible to decrease mineral fertilization under plants grown in that system. At Brody Research Station, the tillage systems did not exert any significant effect on the content of available forms of phosphorus in either analyzed layer, which may be related to the very high initial contents of this element in this soil.

Our results suggest that conservation tillage systems lead to progressive improvement in soil nutrient status, but have little or no effect on crop yield. In the 4-year means, the grain yield of spring barley was significantly lower (by 6.8%) under NT relative to CT, but the yield in RT and CT ranged over a similar level.

Growth and yield of plants did not show any explicit reactions to the applied soil tillage system because they depend on many factors, including soil and climatic conditions, cropping system, selection of pesticides, and the types of machines applied in tillage and sowing (Derpsch 2007). Most studies on cereal production comparing conventional and conservation tillage have given inconsistent results, apparently depending on soil type, crop rotation, and local climatic conditions (Angas et al. 2006; Martin-Rueda et al. 2007). Studies carried out by Małecka et al. (2004) indicate that the yield of spring barley decreased by 8% when plowing tillage was replaced by reduced tillage, and it decreased by 12% when no-tillage was applied. In another experiment (Martin-Rueda et al. 2007) over a shorter research cycle, the same effect was obtained: the yield of spring barley was significantly lower, by 29% in RT and by 17% in NT, relative to CT. In a long-term experiment carried out in Scotland, on average for a period of 24 years of reduced tillage system application, no-tillage decreased the yield of barley grain in the first years of the experiment by 9.2%; however, at the end of the study, the negative response decreased to 4.2% (Soane and Ball 1998). Other authors have reported the same effect on barley yield under tillage systems (Angas et al. 2006; Machado et al. 2007). Arshad and Gill (1997) described the favorable influence of RT (yield increase by 10%) and NT (increase by 12%) on barley yield in dry years in relation to CT, which may have been due to better soil moisture conditions in RT and NT. This finding is not in agreement with our studies, where the effects of different tillage systems were connected to a higher degree with the plant population obtained after planting than with the total precipitation during the vegetation period. In the years when the number of plants after planting was similar in the analyzed systems, no significant differences in plant yields were found between the tillage systems. In conservation tillage systems, postharvest residues left on the field surface in addition to mechanical difficulties in seed placement have often been considered responsible for the low yields obtained with reduced and no-tillage systems. Negative responses to RT and NT may also result from a smaller uptake of nitrogen by plants caused by its immobilization in the soil, lower temperatures in the spring period, higher soil bulk density, and penetration resistance of the soil impeding the development of the plant root system (Angas et al. 2006).

Numerous experiments performed to compare the effect of tillage systems on the yield components of cereals have given different results. According to some of the reports discussed above, reductions in soil tillage lead primarily to a decrease in plant density in the tillering and in the number of ears per square meter, and, in consequence, to a decrease in cereal yield. This has been confirmed by the present study. A lower number of ears per square meter in NT is often compensated for by greater 1000-grain weight (Jug et al. 2011; Małecka et al. 2004), which is in accord with our results.

Continuous cultivation for 7 consecutive years using reduced tillage and no-tillage systems led to changes in the physical properties of the surface soil layer (0-5 cm). At the stem elongation growth stage of spring barley, conservation tillage systems resulted in higher water content and bulk density in relation to conventional tillage. Furthermore, the conservation tillage resulted in decreased penetration resistance in the 0-10 cm layer as compared with CT. However, directly below the subsurface layer (20-30 cm), the penetration resistance of the tilled soils was higher than in the nontilled plots. Present results show the favorable effect of reduced tillage and no-tillage systems in increasing organic C, total N, and nutrient state (K and Mg) of the surface soil layer, when compared with conventional tillage. The conservation tillage systems led to progressive improvement in soil nutrient status, but had little or no effect on crop yield. Only the no-tillage system had a negative effect on the yield of spring barley, reduced by 6.8% in comparison with conventional tillage. The decrease in yield under NT was obtained through a lower number of ears per unit area. In turn, higher grain plumpness in NT resulted in a decreased negative response to this tillage system.

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