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Effect of different tillage systems and straw management on some physical properties of soil and on the yield of winter rye in monoculture**

J. Pabin[1], J. Lipiec[2], S. Włodek[1], and A. Biskupski[1]*

[1]Institute of Soil Science and Plant Cultivation, 55-230 Jelcz-Laskowice, Poland
[2]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, P.O. Box 201, 20-290 Lublin 27, Poland

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A b s t r a c t. Field experiments were conducted on Orthic Luvisol derived from loamy sand in 1999–2002. The tillage systems applied were: conventional tillage (CT) including pre-plough (10 cm) + harrowing, mouldboard ploughing (25 cm) + harrowing; reduced or conservation tillage (RT) using tillage aggregate consisting of a grubber (10 cm) + heavy harrow and string roller; and no-tillage (NT) where the only soil disturbance was from the direct sowing machine. Two straw management systems for the winter rye monoculture were applied on each tillage system: removed straw after harvest and retained straw. The straw was furrowed under CT, shallowly incorporated (7 cm) under RT and remained as chaff under NT. The physical behaviour of the soil was characterised by soil wetness, bulk density and penetration resistance. Under RT and NT with greater soil bulk density compared to CT, the water content of the soil was greater shortly after rainfall only; later, the reverse was true due to enhanced evaporation. The lower water content in the soil and the higher bulk density resulted in increased mechanical impedance for root growth. Retaining the straw did not counteract the negative response in the soil's physical conditions. The effects of the soil tillage and straw management systems on the yields of winter rye in monoculture were considerably affected by rainfall distribution during the growing seasons. In growing seasons with dry periods, the crop yield was more reduced under RT and NT than CT and on 'straw-retained' than 'straw-removed' plots. However, in growing seasons with favourable rainfall distribution, the crop yield was not negatively affected by the RT and NT systems.

K e y w o r d s: conventional tillage, reduced tillage, straw management, soil, winter rye

INTRODUCTION

In Poland, about 30% of coarse-textured arable soils with inherently low fertility is suitable for rye production. At present, the profitability of the agricultural use of such soils is very low and therefore they are often abandoned. Numerous experiments performed on fine textured soils have revealed that reducing the intensity of tillage by decreasing tillage depth and the number of tillage operations or applying a no-tillage system results in considerably lower crop production costs [7, 24]. The successful application of reduced tillage systems on sandy soils could provide an opportunity to improve the profitability of the agricultural use of such soils, especially in farms without livestock; the same could be said for applying a monoculture practice for winter rye whilst retaining the crop residue on the field. Furthermore, the long-term use of reduced tillage in some regions could provide conditions for environmentally sound production [23]. Retaining or adding crop residue improves several physical, biological and chemical characteristics and thereby increases soil quality [6, 8]. These effects are related to the tillage system used. Soil water and strength characteristics are identified as the main properties influencing the physical quality of the soil after cultivation and crop residue management. With time, changes in characteristics provide information on the sustainability of the soil [12].

The aim of this study was to evaluate the effects of simplified tillage systems and different techniques of straw management on the physical properties of sandy soil and the crop yield of winter rye cultivated in monoculture.

MATERIALS AND METHODS

Field experiments (1999–2002) were conducted on Orthic Luvisol of loamy sand texture (7% of particles <0.02 mm), low in organic matter (0.77% Corg.) and acid (pH in

*Corresponding author's e-mail: zakljl@mikrozet.wroc.pl

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KCl = 5.5) at the Experimental Station of the Institute of Soil Science and Plant Cultivation in Jelcz-Laskowice (51° 03' N; 17° 21' E). The soil is relatively high in phosphorus (24.3 mg P_2O_5/100 g of soil), potassium (17.2 mg K_2O/100 g of soil) and magnesium (6.2 mg MgO/100 g of soil).

Two factors, i.e., tillage systems and straw management were investigated under continuous winter rye monoculture. Three tillage systems were applied, conventional tillage (CT): including pre-plough (10 cm) + harrowing, mouldboard ploughing (25 cm) + harrowing; reduced or conservation tillage (RT): using tillage aggregate consisted of grubber (10 cm) + heavy harrow and string roller; and no-tillage (NT) where the only soil disturbance results from a direct sowing machine. The use of monoculture was chosen because it is becoming an increasingly used practice in Poland. Under each tillage treatment two straw management systems were applied: retained straw and removed straw. The straw retained under CT was covered by furrows while ploughing, shallowly incorporated (7 cm) under RT and under NT it was cut to the chaff and retained as a surface residue. This suggests that the carbon input was considerably greater in the 'straw-retained' plots than the 'straw-removed' plots. The rye varieties used were: Motto in 1999; Dańkowskie Złote in 2000 and 2002 and Amilo in 2001. Mineral fertilisation including 96 kg N, 60 kg P_2O_5 and 90 kg K_2O per hectare was applied each year. In 2001, 2 Mg ha^{-1} of magnesium calcium (50% CaO + MgO) was applied on the whole experimental field. The weeds were controlled solely by herbicides under NT and by tillage operations under RT and CT. When tillage operations were not efficient enough more herbicides were applied.

Measurements of the penetration resistance, bulk density and the water content of the soil were taken at the beginning of the shooting growth phase and at the beginning of the appearance of the grain each year except in 2000 on account of the late appearance of the grain because of drought. Penetration resistance was determined in 5 cm layers to a depth of 30 cm using a drop-cone penetrometer. The plummet mass, weighing 2170 g, hit the cone with a diameter of 2.4 cm and at a 30° angle from a height of 25 cm. Bulk density was determined by the core method [3] at depths: 0–5, 10–15 and 20–25 cm using 100 cm^3 cores (in 10 replicates). The same cores were used to determine the gravimetric water content in the soil.

As can be seen from Table 1 extremely low rainfall occurred during late autumn (XI, XII 1998); autumn (IX, X, XI 1999 and IX, X 2000) spring/summer period (V, VII 1999; IV, VI 2000 and VI, VII 2002). The scarcity of rainfall during the spring and summer months was accompanied by higher temperatures. The interactive effects of both factors on plant growth were exacerbated by these drought conditions. Only in 2001 were there no drought symptoms.

A statistical analysis of the results was performed using the Anovan programme.

RESULTS AND DISCUSSION

Soil water

Tillage systems influenced the water content of the soil by altering the bulk density and the associated water movement and evaporation. On 3 out of 7 occasions, the highest water content in the soil was observed under CT and the lowest under RT (Table 2). The differences were significant. Similar results have been identified in other experiments [4, 10, 15, 23, 25]. On three occasions (shooting in 1999 and 2000 and at the appearance of the grain in 2001) no significant differences in the tillage systems were observed

T a b l e 1. Month and year air temperature means T (°C) and month and year rainfall sums R (mm) at Jelcz-Laskowice

Year		Month												Year value
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1998	R	41.1	22.9	40.8	46.0	27.6	91.6	117.2	41.6	94.7	82.2	30.4	17.5	653.6
	T	1.3	4.1	2.8	10.4	14.6	18.0	18.2	17.4	13.4	8.6	0.1	-0.7	9.0
1999	R	21.6	49.4	57.7	56.4	35.6	79.1	17.4	183.6	33.5	24.3	36.3	36.1	631.0
	T	1.1	-0.5	5.0	9.6	14.0	16.6	17.7	19.9	16.5	9.1	2.2	1.3	9.4
2000	R	34.6	33.5	76.9	17.8	76.5	38.1	165.8	45.4	17.3	10.9	47.9	34.8	599.5
	T	-1.0	3.3	4.7	11.8	15.6	18.1	16.7	18.5	12.8	12.1	6.5	2.0	10.1
2001	R	20.7	18.1	60.3	40.9	68.8	71.0	140.8	46.7	79.2	22.5	33.2	-2.2	633.6
	T	0.0	0.9	3.2	7.7	14.8	15.1	19.2	19.4	12.5	12.1	3.4	31.4	8.9
2002	R	24.0	58.2	15.9	44.5	78.8	53.7	38.2	85.5	32.7	63.3	47.5	19.7	562.0
	T	-0.2	4.3	5.0	8.3	17.2	18.1	20.5	20.4	13.0	7.7	4.8	-4.2	9.6
1961-	R	27.9	25.2	31.6	36.9	63.8	71.5	75.4	70.6	47.8	36.9	41.1	35.1	563.7
2000	T	-1.5	-0.3	3.3	8.2	13.4	16.6	18.1	17.6	13.5	8.8	3.7	0.2	8.5

and only in one case was the water content of the soil under reduced tillage treatments (RT and NT) greater than in CT (grain setting, 2002). This is in contrast to the results reported from other experiments performed mostly on fine-textured soils [1, 2, 5, 14, 18, 19]. In other longterm experiments on the same soil [16], however, no significant effects of the various tillage systems on the soil to water relations were observed. This implies that the effects observed in this study might be casual in character.

The effect of different straw management techniques on the soil's water content was not uniform throughout (Table 2). As indicated by the mean values for all tillage treatments, retaining the rye straw after harvest reduced evaporation only in periods of drought (at the shooting stage, 2000 and grain setting, 2002) which could be the result of slower drying compared to bare soils [8]. The positive effect of retaining straw – which holds water in dry conditions – has been confirmed on other sites where it resulted in a substantial increase of crop yield [20–22]. However, in wetter periods in this study (e.g., grain setting, 1999 and shooting, 2002,) a higher than average water content in the soil was observed mostly on the 'straw-removed' plots as opposed to the 'straw-retained' plots. The opposite effects of straw management systems on respective occasions meant that the 4-year average treatment was very smooth and statistically insignificant.

The effect of straw management on the water content of the soil was related to the tillage system (Table 2). The water content of the soil was greater on the 'straw-removed' plots than on the 'straw-retained' plots on all occasions under CT and on most occasions under NT. On most occasions, straw management with the addition of tillage interaction was significant. However, the effect of straw was less consistent under RT, which was reflected in the same 4-year average water content (9.9 %, w/w) in the 'straw-removed' and the 'straw-retained' plots.

It is important to note that occasionally, the effect of the retained straw on the water content of the soil was positive under NT or RT but negative under CT (e.g., at the shooting stage in 2001). These opposite effects were associated with the different functions of the straw in respective tillage systems. Under NT, chaff retained on the soil surface reduced evaporation but when rainfall was minimal it absorbed part of the rainwater, thereby limiting water penetration to deeper and rooted soil. However under CT, the straw covered by furrows during ploughing increases the organic matter content of the soil and thereby the capacity for storing water. The effects of the straw can be similar under RT where incorporation is shallow. The sporadically inconsistent effects of experimental treatments on the water content of the soil are highly influenced by the amount of precipitation, the water infiltration rate into the deeper soil profile and the evaporation rate [16]. These interrelations limit the predictability of the effects of the treatment.

Table 2. Effect of different tillage and straw management systems on soil water content (%,w/w) in 0–25 cm layer

Straw	Tillage	Date							Mean
		1999		2000	2001		2002		
		I	II	I	I	II	I	II	
Left	conventional	8.8	14.9	6.2	14.3	9.2	12.7	4.2	10.0
	reduced	9.4	13.2	6.3	13.1	10.0	11.8	5.8	9.9
	no-till	8.4	12.9	6.4	14.2	8.6	12.0	5.2	9.7
	mean	8.9	13.7	6.3	13.8	9.3	12.2	5.1	9.9
Removed	conventional	9.5	16.3	6.6	15.6	10.2	13.3	4.4	10.8
	reduced	9.9	14.5	5.8	12.7	9.6	12.8	4.3	9.9
	no-till	9.8	15.2	5.7	13.6	10.5	12.6	4.8	10.3
	mean	9.7	15.3	6.0	13.9	10.1	12.9	4.5	10.3
Mean	conventional	9.2	15.6	6.4	15.0	9.7	13.0	4.3	10.5
	reduced	9.7	13.8	6.0	12.9	9.8	12.3	5.0	9.9
	no-till	9.1	14.0	6.0	14.2	9.6	12.3	5.0	10.0
$LSD_{(0.05)}$									
tillage (t)		n.s.	0.75	n.s.	0.57	n.s.	0.56	0.51	n.s.
straw (s)		0.42	0.40	0.30	n.s.	0.30	0.30	0.28	n.s.
interaction (t s)		n.s.	0.69	0.52	0.52	0.52	n.s.	0.48	n.s.

I – beginning of shooting, II – beginning of grain setting, n.s. – not significant.

Bulk density

Tillage and straw management systems had an influence on the bulk density of the soil (Table 3). On 4 out of 7 occasions the average soil bulk density under NT and RT was significantly (0.05) greater than under CT. The effect of the retained straw was most pronounced on 3 occasions. On one occasion, – in 2000 – the straw led to an increase in bulk density whereas on another two occasions in 2002 – it led to a decrease in bulk density. It is important to note that the decrease being 0.03–0.07 g cm^{-3} was greater than the increase 0.02 g cm^{-3}. Although the differences were relatively small they were statistically significant indicating the small dispersion of the results. This decrease was due mostly to a substantial reduction in bulk density on NT plots where straw acting as mulch protected the soil's structure against the destructive impact of the rain. This protective effect of the straw mulch has been reported on earlier studies [19].

The interactive effects of the tillage and straw management systems on soil bulk density increased with the duration of the experiment. This is confirmed by the statistically significant interaction (tillage with the addition of straw management) (0.05) during 2001 and 2002 in contrast to 1999 and 2000 (Table 3). This inconsistency could be associated with the uneven distribution of the straw on the surface of the soil. As a consequence, the interaction systems were not significant for the whole 4-year period.

Penetration resistance

Penetration resistance has been influenced by the tillage systems (Table 4). Generally, its values were higher under reduced tillage systems (RT and NT) than under CT. The differences were significant on 3 out of 7 occasions. Retaining the straw had a significant effect on penetration resistance but only at the beginning of the shoot-growth phase in 1999 and at the appearance of the grain in 2001. In the first case, it was greater on the 'straw-retained' (4 MPa) than on the 'straw-removed' plots (3 MPa) which could be attributed to the lower water content of the soil of the former (Table 2). This effect was opposite in the second case where penetration resistance was increased in both the 'straw-retained' and the 'straw-removed' plots.

Winter rye yield

The effects of the tillage system and straw management on the yield of winter rye grain over 4 consecutive years are shown in Table 5. In the growing seasons (1998/99, 1999/00, 2001/02) with their spring and autumn droughts, crop yields under the reduced tillage systems (RT and NT) were significantly lower than under the CT system. On average, the reduction was approximately 14.4%. The yield reduction in the dry periods could partly be attributed to the shallow rooting depth and greater stomatal resistance in response to an insufficient water supply to the plants. This was observed by Lipiec and Gliński [11] during the growing

T a b l e 3. Effect of different tillage and straw management systems on soil bulk density (g cm^{-3}) in 0–25 cm layer

Straw	Tillage	Date 1999 I	1999 II	2000 I	2001 I	2001 II	2002 I	2002 II	Mean
Left	conventional	1.41	1.40	1.40	1.36	1.40	1.41	1.35	1.39
	reduced	1.44	1.50	1.40	1.46	1.43	1.43	1.41	1.43
	no-till	1.42	1.48	1.41	1.44	1.47	1.38	1.41	1.43
	mean	1.42	1.46	1.40	1.42	1.43	1.41	1.39	1.42
Harvested	conventional	1.40	1.40	1.36	1.44	1.40	1.43	1.43	1.41
	reduced	1.36	1.47	1.39	1.44	1.48	1.41	1.45	1.39
	no-till	1.39	1.45	1.38	1.45	1.44	1.48	1.50	1.43
	mean	1.39	1.44	1.38	1.44	1.44	1.44	1.46	1.42
Mean	conventional	1.41	1.40	1.38	1.40	1.40	1.42	1.35	1.40
	reduced	1.40	1.49	1.40	1.45	1.46	1.42	1.41	1.44
	no-till	1.41	1.47	1.40	1.45	1.46	1.43	1.41	1.44
$LSD_{(0.05)}$									
tillage (t)		n.s.	0.03	n.s.	0.03	0.04	n.s.	0.04	n.s.
straw (s)		n.s.	n.s.	0.02	n.s.	n.s.	0.02	0.02	n.s.
interaction (t s)		n.s.	n.s.	n.s.	0.03	0.03	0.04	0.04	n.s.

Explanations as in Table 1.

T a b l e 4. Effect of different tillage and straw management systems on penetration resistance (MPa) in 0–25 cm layer

Straw	Tillage	Date							Mean
		1999		2000	2001		2002		
		I	II	I	I	II	I	II	
Left	conventional	3.6	2.3	4.8	2.7	4.0	3.9	6.2	3.9
	reduced	4.0	3.4	5.3	3.5	4.5	6.1	5.7	4.6
	no-till	4.4	3.1	5.3	3.5	4.7	4.3	7.3	4.7
	mean	4.0	2.9	5.1	3.2	4.4	4.8	6.4	4.4
Removed	conventional	2.6	1.6	7.0	2.5	6.7	3.7	6.6	4.4
	reduced	3.1	3.3	5.7	3.4	4.8	5.5	7.2	4.7
	no-till	3.4	3.3	5.2	3.4	5.1	4.0	7.1	4.5
	mean	3.0	2.7	6.0	3.1	5.5	4.4	7.0	4.5
Mean	conventional	3.1	2.0	5.9	2.6	5.4	3.8	6.4	4.2
	reduced	3.6	3.4	5.5	3.4	4.6	5.8	6.4	4.7
	no-till	3.9	3.2	5.3	3.4	4.9	4.2	7.2	4.6
$LSD_{(0.05)}$									
tillage (t)		n.s.	0.73	n.s.	0.72	n.s.	0.99	n.s.	n.s.
straw (s)		0.59	n.s.	n.s.	n.s.	0.86	n.s.	n.s.	n.s.
interaction (t s)		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Explanations as in Table 1.

T a b l e 5. Effect of different tillage systems and straw management on grain yield of winter rye (Mg ha^{-1})

Straw	Tillage	1999	2000	2001	2002	Mean
Left	conventional	3.78	3.19	4.72	3.06	3.69
	reduced	2.98	3.11	4.55	2.94	3.40
	no-till	2.62	2.96	4.43	2.67	317
	mean	3.12	3.09	4.57	2.89	3.42
Harvested	conventional	4.02	3,60	4.76	3.08	3.87
	reduced	2.90	3.08	4.58	2.59	3.29
	no-till	3.24	2.86	4.58	3.20	3.47
	mean	3.38	3.18	4.64	2.96	3.54
Mean	conventional	3.90	3.40	4.74	3.07	3.78
	reduced	2.94	3.10	4.57	2.77	3.34
	no-till	2.93	2.91	4.51	2.94	3.32
$LSD_{(0.05)}$						
tillage (t)		0.62	0.31	n.s.	0.27	0.47
straw (s)		0.33	0.16	n.s.	n.s.	n.s.
years (y)						0.47
interaction:	t x s	n.s.	0.29	n.s.	0.25	n.s.
	t x y	n.s.	n.s.	n.s.	n.s.	n.s.
	s x y	n.s.	n.s.	n.s.	n.s.	n.s.

Explanations as in Table 1.

season of wheat. In dry seasons, crop yield on 'straw-retained' plots was less by up to 4.3% than was the case for 'straw-removed' plots.

The interactive effect of tillage and straw management systems on crop yields was significant in two dry seasons (1999/00 and 2001/02). This interaction indicates that the effect on winter rye yields from retaining the straw was negative in 2000 under CT and in 2002 under NT. However, retaining the straw under RT had a positive effect on the crop yield in most years. The results indicate that this yield's increase is accidental and can be more associated with its reduction on 'straw-removed' plots than with its increase on 'straw-retained' plots.

Crop yields in all tillage and straw management systems were highest in 2001 with its relatively high total rainfall and its favourable distribution during the growing season. Compared to yields in other years where there were water shortages, they were greater on average by 31%. In addition this year, the effects of both the tillage and straw management did not have a significant effect on grain yield. This implies that reduced tillage systems can be applied without a negative effect on crop yield even on light soils provided that the weather favours plant growth. This may refer not only to the winter rye monoculture, but also to crop rotation as shown in earlier studies [17]. Since reduced tillage systems demand low energy compared to conventional tilling systems they can improve the profitability of winter rye cultivation given a sufficient supply of water for the plants. In addition reduced tillage systems are considered more advantageous from the point of view of environmental protection [9,13, 23].

CONCLUSIONS

1. The 4-year application of reduced tillage, including the no-tillage option resulted in the greater bulk density of the soil and its penetration resistance. These increases in growing seasons with spring and autumn dry periods, result in reduced plant growth and crop yield. Leaving the straw – as is the case in the reduced tillage systems – did not counteract the negative changes in the parameters of the soil's strength.

2. Changes in the water content of the soil under the tillage and straw management systems are related to soil bulk density and weather conditions during the growing season. Compared to CT, water storage was greater under reduced tillage systems with greater soil bulk density, but only for short periods after rainfall. However, in periods with relatively scarce rainfall, the reverse was true because of increased evaporation from denser soil.

3. The effect of the straw – which was retained – on the conservation of water in the soil is positive in periods with scarce rainfall due to the slow rate of evaporation. However, in periods with greater rainfall, some water is absorbed by the straw and thereby reduces the quantity of rainwater penetrating the soil.

4. With regard to crop yield, the response of the winter rye monoculture to treatments applied to the sandy soil – which is of low water holding capacity and low inherent fertility – was largely associated with weather conditions during the growing season. In periods of favourable rainfall distribution, the application of reduced tillage systems and retaining straw on the field did not cause any reduction in crop yields. However, in growing seasons afflicted by drought, the application of reduced tillage systems resulted in a significant reduction of yields relative to conventional tillage. In such periods, retaining the straw after the harvest negatively affected crop yield also.

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