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The Effects of Soil Compaction and Different Tillage Systems on the Bulk Density and Moisture Content of Soil and the Yields of Winter Oilseed Rape and Cereals

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Abstract: Progressive soil compaction is a disadvantage of intensive tillage. Compaction exerts a negative impact on the physical properties of soil and decreases crop performance. The adverse effects of soil compaction can be mitigated by replacing conventional tillage with simplified tillage techniques. Simplified tillage exerts a protective effect on soil, reduces production costs and preserves agricultural ecosystems. The aim of this study was to determine the influence of compaction and different tillage methods on the bulk density and moisture content of soil. The experimental factors were as follows: Soil compaction before sowing (non-compacted control treatment and experimental treatments where soil was compacted after the harvest of the preceding crop) and four different methods of seedbed preparation in a three-field rotation system (winter oilseed rape, winter wheat, spring barley). The influence of compaction on the bulk density and moisture content of soil varied across the rotated crops and their developmental stages. Soil compaction had no significant effect on the analyzed parameters in the cultivation of winter oilseed rape. In treatments sown with winter wheat, soil compaction resulted in significantly lower soil density and significantly higher soil moisture content. In plots sown with spring barley, soil compaction led to a significant increase in the values of both parameters. The average bulk density of soil after various tillage operations in the examined crop rotation system ranged from 1.49–1.69 $g \cdot m^{-3}$ (winter oilseed rape), 1.47–1.59 $g \cdot m^{-3}$ (winter wheat), 1.47–1.61 $g \cdot m^{-3}$ (spring barley). The bulk density and moisture content of soil were lowest after conventional tillage (control treatment) and higher after simplified tillage. Regardless of soil compaction, the greatest reduction in winter oilseed rape yields was noted in response to skimming, harrowing and the absence of pre-sowing plowing. Spring barley yields were higher in non-compacted treatments, whereas the reverse was observed in winter wheat. Chisel plowing and single plowing induced the greatest decrease in wheat yields relative to conventional tillage. Single plowing significantly decreased the grain yield of spring barley relative to the tillage system that involved skimming and fall plowing to a depth of 25.

Keywords: yield; physical properties of soil; crop rotation; plant growth stages; wheat; spring barley

1. Introduction

Soil tillage exerts a considerable influence on growing conditions and crop performance, and it is performed mainly to optimize soil productivity by modifying its chemical, physical and biological properties [1–5]. Tillage should counteract the adverse effects of technological progress and agricultural mechanization, in particular soil compaction. Conventional tillage (plowing), seedbed preparation and soil treatments where agricultural machines and devices move repeatedly across the field increase soil compaction [6,7]. Heavy agricultural machines damage soil aggregates, increase soil density and moisture content, and decrease soil porosity and permeability [8–10]. Already in the 1970s, Byszewski and Haman [11] demonstrated that field operations involving a tractor with a weight of more than 2 tons increased soil density from 1.57 to 1.68 g/cm^{-3}. The main factors that contribute to soil compaction are heavy wheel loads and the number of tractor passes in the field [9]. Soil compaction compromises aeration and the water-holding capacity of soil, and induces changes in its chemical and biological properties [12,13], leading to soil degradation and decreased crop yields [5,14–16]. The adverse effects of soil compaction are visible not only in the arable layer. Deeper soil layers are also compacted, which can lead to the formation of plow pans that are very difficult to eliminate [17].

In contemporary agriculture, attempts are being made to replace energy-intensive plowing with simplified tillage, to reduce the number and intensity of soil tillage and loosening operations, or even completely eliminate these practices [18]. Such an approach exerts protective effects on the soil, contributes to preserving the natural value of agroecosystems and reducing production costs [1,5,19]. However, under long-term no-tillage system, previous ploughpan layer remains compacted, and a layer to 20 cm has high bulk density, low porosity, and high mechanical resistance [20,21].

To promote the development of sustainable agriculture, the combined effects of soil compaction, simplified tillage and crop rotation should be investigated to design cropping systems that maximize yields and minimize soil degradation [22].

The aim of the present study was to evaluate the effects of soil compaction and different tillage systems on the bulk density and moisture content of soil sown with winter oilseed rape, winter wheat and spring barley.

2. Materials and Methods

2.1. Field Experiment

A small-area, long-term, two-level factorial field experiment was conducted in the Agricultural Experiment Station in Bałcyny (53°36′ N, 19°51′ E; eastern Poland) owned by the University of Warmia and Mazury in Olsztyn. The experiment had a strip-plot design with four replications, and it was carried out in 2009–2011. Plot size was 30 m^2. The experiment was established on Haplic Luvisol (Aric, Ochric) developed from loamy sand (LS) underlain by sandy loam (SL)IUSS Working Group WRB [23]. The topsoil (0–20 cm) was slightly acidic (pH_{KCl} 5.5), and its organic carbon content ranged from 10 to 10.7 $g \cdot kg^{-1}$, phosphorus content—from 74.0 to 82.1 mg·kg (moderate), potassium content—from 98.2 to 160.1 mg·kg (low to moderate), and magnesium content—from 36.1 to 39.0 mg·kg (low). The granulometric composition of soil was the only physical parameter that was determined before the experiment. Soil contained the following particle-size fractions: <0.002 (3.71%), 0.002–0.005 (4.40%), 0.005–0.010 (5.55%), 0.010–0.020 (8.38%), 0.020–0.050 (16.79%), 0.050–0.100 (18.18%), 0.100–0.250 (25.10%), 0.250–0.500 (14.3%), 0.500–1.00 (3.59%). Particle-size fractions were determined with the Mastersizer 2000 laser diffraction particle size analyzer.

Four tillage methods were compared in a three-field rotation system involving the following crop species: Winter oilseed rape (cv. Mendel), winter wheat (cv. Ludwig) and spring barley (cv. Justina). The experimental factors were: Soil compaction before sowing (non-compacted control treatment), treatments where soil was compacted after the harvest of the preceding crop (tractor and trailer with a combined weight of approx. 6 tons) and four methods of seedbed preparation for the tested crops.

The analyzed tillage systems, and the combination and sequence of seedbed preparation treatments in the production of winter oilseed rape and cereals:

Winter oilseed rape:

- Conventional tillage system U-1 (control). After harvesting of the preceding crop: Skimming (10 cm) + harrowing; before sowing: Pre-sowing plowing (20 cm).
- Tillage system U-2. After harvesting of the preceding crop: Chisel plow (40 cm) + disk cultivator + harrowing + cultivation; before sowing: Pre-sowing plowing (20 cm).

- Tillage system U-3. After harvesting of the preceding crop: Skimming (10 cm) + harrowing.
- Tillage system U-4. Before sowing: Single plowing (30 cm).
- Winter wheat:
- Conventional tillage system U-1 (control): After harvesting of the preceding crop: Skimming (10 cm) + harrowing; before sowing: Pre-sowing plowing (20 cm).
- Tillage system U-2. After harvesting of the preceding crop: Rotary cultivator; before sowing: Pre-sowing plowing (20 cm).
- Tillage system U3. After harvesting of the preceding crop: Disk cultivator + harrowing + cultivation; before sowing: Pre-sowing plowing (20 cm).
- Tillage system U-4. After harvesting of the preceding crop: Chisel plow (40 cm); before sowing: Single plowing (30 cm).
- Spring barley:
- Conventional tillage system U-1 (control). After harvesting of the preceding crop: Skimming (10 cm) + harrowing; before winter: Fall plowing (30 cm).
- Tillage system U-2. After harvesting of the preceding crop: Skimming (10 cm) + harrowing + cultivation; before winter: Fall plowing (25) cm.
- Tillage system U-3. After harvesting of the preceding crop: Cultivator; before winter: Fall plowing (25–30) cm.
- Tillage system U-4. Before winter: Single plowing (30 cm

The following seeding rates were applied: Winter oilseed rape—65 plants$\cdot$m^{-2}, winter wheat—400 plants$\cdot$m^{-2}, spring barley—320 plants$\cdot$m^{-2}. Only mineral fertilizers were applied, at the following rates (kg$\cdot$ha^{-1}): Winter oilseed rape: N—180, P—80 and K—120; winter wheat: N—50, P—80 and K—120; spring barley: N—80, P—70 and K—100. Weeds, pathogens and pests were controlled chemically, subject to need. The latest crop protection agents were applied according to the recommendations of the Institute of Plant Protection in Poznań. Seeds were sown with a Väderstad seed drill in all treatments.

2.2. Measurements of the Physical Properties of Soil

The bulk density and moisture content of soil were analyzed in undisturbed soil samples. Soil was sampled to a depth of 0–20 cm, in two horizons: 0–10 cm and 10–20 cm. Samples were collected into 100 cm^3 Kopecky cylinders, and they were dried at a temperature of 105 °C until constant weight. Soil moisture content was determined with the use of the following formula: $W = (A - B)/(B - C) \times 100$, where A—is the weight of the cylinder with soil and water upon sample collection [g]; B—is the weight of the cylinder with soil after drying at 105 °C [g]; C—is the weight of an empty cylinder (tare weight) [g]. The bulk density of moist soil was calculated with the following formula: $S = (B - C)/100$, where B—is the weight of the cylinder with soil after drying at 105 °C [g]; C—is the weight of an empty cylinder (tare weight) [g]. In all plots, all measurements were made in four replicates on three dates: At the beginning of the spring growing season of winter crops (winter oilseed rape and winter wheat—4 April), in the early growth stages of spring barley (6 April, BBCH 09–11), during the flowering of winter oilseed rape (4 May, BBCH 62–65), during stem elongation in winter wheat (13 April) and spring barley (20 April, BBCH 31–33), and after the harvest of winter oilseed rape (8 July, BBCH 89), winter wheat (12 August) and spring barley (11 July, BBCH 89–92).

In each plot, all measurements were performed in four replications on three dates: At the beginning of the spring growing season of winter crops and in the early growth stages of spring barley (BBCH 9–11), during the flowering of winter oilseed rape (BBCH 62–65), during stem elongation in winter wheat and spring barley (BBCH 31–33), and after the harvest of winter oilseed rape (BBCH 89), winter wheat and spring barley (BBCH 89–92).

After the harvest of winter oilseed rape, winter wheat and spring barley, seed and grain yields were determined in each plot (in kg per plot) and adjusted to 14% moisture content. The results were expressed per hectare.

2.3. Statistical Analysis

The results of the field experiment with a strip-plot design model were processed by two-way ANOVA, where soil compaction and tillage systems were the fixed effects. The significance of differences between means was evaluated by Tukey's honest significant difference (HSD) test. Statistical analyses were conducted in the Statistica 13.3 program [24] at a significance level of $\alpha = 0.05$

2.4. Weather Conditions

Meteorological data were obtained from the Meteorological Station in Bałcyny (53°36′ N, 19°51′ E; eastern Poland). Weather conditions were determined based on the mean daily temperature and precipitation levels. Air temperature was measured 2 m above the ground.

Weather conditions varied during the experiment (Table 1). During the growing season of winter oilseed rape in fall, total precipitation exceeded the long-term average (measured in the vicinity of the experimental station in Bałcyny) by more than 19% (by 36.4 mm). August and October were extremely wet months, whereas in September, precipitation was 42.1 mm below the long-term average. Between April and July, mean air temperature (13.9 °C) and total precipitation (308.6 mm) exceeded the long-term average by 0.8 °C and 64.5 mm, respectively. In April, precipitation levels were 9.5 times lower than the long-term average, whereas in May and June, total precipitation exceeded the long-term average 1.5-fold and nearly 2-fold, respectively. In July, precipitation levels were also above the long-term average. During the growing season of winter wheat in spring, mean air temperature and total precipitation exceeded the long-term average by 10% and 15%, respectively. March and April of 2010 were warm (2.1 °C and 7.9 °C, respectively) and dry months, and in April, precipitation was 26 mm lower than the long-term average. In May, total precipitation (105.5 mm) exceeded the long-term average by 48 mm. Due to high temperatures in June and very high temperatures in July, winter wheat grain achieved the fully ripe stage in the last 10 days of July.

Table 1. Mean air temperature and precipitation during the growth of winter oilseed rape and cereals.

Years	**Month**									**Total/ Mean July–Oct**	**Total/ Mean Apr–July**
	Aug	**Sept**	**Oct**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**		
Winter oilseed rape											
Precipitation (mm)											
2008/2009	103.1	17.0	104.6	x	3.7	89.6	133.1	82.2	x	224.7	308.6
1962–2002	75.2	59.1	54.0	x	35.4	57.6	69.5	81.6	x	188.3	244.1
Mean air temperature (°C)											
2008/2009	17.7	11.9	8.6	x	9.7	12.2	14.7	18.9	x	12.7	13.9
1962–2002	16.8	12.6	8.1	x	7.0	12.5	15.8	17.2	x	12.5	13.1
Winter wheat											
Precipitation (mm)											
2010	x	x	x	23.8	9.4	105.5	73.7	87.8	99.3	x	399.5
1962–2002	x	x	x	26.8	35.4	57.6	69.5	81.6	75.2	x	346.1
Mean air temperature (°C)											
2010	x	x	x	2.1	7.9	12.0	15.7	20.8	19.3	x	13.0
1962–2002	x	x	x	1.3	7.0	12.5	15.8	17.2	16.8	x	11.8
Spring barley											
Precipitation (mm)											
2011	x	x	x	8.6	33.7	41.5	56.2	171.9	83.6	x	395.5
1962–2002	x	x	x	26.8	35.4	57.6	69.5	81.6	75.2	x	346.1
Mean air temperature (°C)											
2011	x	x	x	2.0	9.7	13.6	17.5	18.0	18.1	x	13.2
1962–2002	x	x	x	1.3	7.0	12.5	15.8	17.2	16.8	x	11.8

In 2011, weather conditions were generally unfavorable during the growing season of spring barley. A dry spell lasted from March and the end of June, and precipitation was lowest in May (41.5 mm) and June (56.2 mm). In May and June, air temperatures exceeded the long-term average by 1.1 °C and 1.7 °C, respectively, which further deepened the water deficit. In July, total precipitation (171.9 mm) exceeded the long-term average more than 2-fold.

During the growing season of winter oilseed rape, October and June were extremely wet months; August and May were characterized by relatively high and high precipitation, respectively, whereas September and April were dry and very dry months, respectively. In the cultivation of winter wheat, March was regarded as an extremely wet month, May was a very wet month, whereas April was a very dry month. June and July were characterized by optimal hydrothermal conditions. During the growing season of spring barley, May was a dry month, April and June were relatively dry months, whereas July was an extremely wet month.

3. Results

At the beginning of the spring growing season of winter oilseed rape, no significant differences were found in soil density at the analyzed depths (0–10 cm and 10–20 cm) between compacted and non-compacted plots or between tillage systems (Table 2). Significant differences were observed when the interactions between the experimental factors were analyzed separately in compacted and non-compacted treatments. In non-compacted plots, soil density was significantly lower (by approx. 10.7%) in the simplified tillage system U-2 (chisel plow, pre-sowing plowing, 20 cm) relative to the control treatment (conventional tillage). In compacted plots, soil density was significantly highest in the simplified tillage system U-2, and significantly lowest in the simplified tillage system U-4 (single plowing, 30 cm). At a depth of 10–20 cm, soil density in compacted and non-compacted plots did not differ significantly between the compared tillage systems.

Table 2. Bulk density of soil at the analyzed depths in selected growth stages of winter oilseed rape (g/cm^3).

Treatment	Tillage Systems				
	Conventional Tillage U-1 (control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
	Date of analysis and measurement depth				
	Beginning of the spring growing season, 0–10 cm				
Not Compacted	*1.67a*	*1.49b*	*1.64ab*	*1.63ab*	1.61 NS
Artificially Compacted	1.60b	1.64a	1.62ab	1.57c	1.61 NS
Mean	1.64 NS	1.57 NS	1.63 NS	1.60 NS	x
	Beginning of the spring growing season, 10–20 cm				
Not Compacted	*1.60 ns*	*1.63 ns*	*1.62 ns*	*1.57 ns*	1.61 NS
Artificially Compacted	1.60 ns	1.66 ns	1.60 ns	1.59 ns	1.61 NS
Mean	1.60 NS	1.65 NS	1.60 NS	1.58 NS	x
	Flowering, 0–10 cm				
Not Compacted	*1.70 ns*	*1.68 ns*	*1.74 ns*	*1.66 ns*	1.70A
Artificially Compacted	1.60 ns	1.66 ns	1.60 ns	1.52 ns	1.60B
Mean	1.65 NS	1.67 NS	1.67 NS	1.59 NS	x
	Flowering, 10–20 cm				
Not Compacted	*1.45b*	*1.66a*	*1.50b*	*1.65a*	1.57B
Artificially Compacted	1.67b	1.64b	1.74a	1.58c	1.66A
Mean	1.56 NS	1.65 NS	1.62 NS	1.62 NS	x

Table 2. *Cont.*

Treatment	Tillage Systems				
	Conventional Tillage U-1 (control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
			After harvest, 0–10 cm		
Not Compacted	*1.74 ns*	*1.54 ns*	*1.58 ns*	*1.68 ns*	1.64 NS
Artificially Compacted	1.60 ns	1.64 ns	1.58 ns	1.69 ns	1.63 NS
Mean	1.67 NS	1.59 NS	1.58 NS	1.69 NS	x
			After harvest, 10–20 cm		
Not Compacted	*1.41 ns*	*1.62 ns*	*1.52 ns*	*1.66 ns*	1.55 NS
Artificially Compacted	1.57 ns	1.54 ns	1.58 ns	1.59 ns	1.57 NS
Mean	1.49 NS	1.58 NS	1.55 NS	1.63 NS	x

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments; ns—not significant.

During the flowering of winter oilseed rape, compaction significantly influenced the bulk density of soil (Table 2). Bulk density was significantly lower at a depth of 10 cm (in compacted plots) relative to the control treatment, whereas the reverse was observed at a depth of 10–20 cm. The overall differences in soil density between the evaluated tillage systems were not statistically significant. Significant differences in soil density were noted only at a depth of 10–20 cm. Soil density was significantly highest in the simplified tillage system U-2 (in non-compacted plots). In compacted plots, soil density was significantly highest in the simplified tillage system U-3 (skimming, 10 cm, and harrowing). After the harvest of winter oilseed rape, the bulk density of soil was not significantly differentiated by the experimental factors at the examined depths (0–10 cm and 10–20 cm) (Table 2).

The analyzed tillage systems induced significant differences in the moisture content of soil at the beginning of the spring growing season of winter oilseed rape (Table 3). Soil moisture content was significantly higher at a depth of 0–10 cm in tillage systems U-1 (conventional tillage) and U-3 (skimming and harrowing after harvest, without pre-sowing plowing) than in the simplified tillage system U-2 (chisel plow, 40 cm, disc cultivator, harrowing, pre-sowing plowing, 20 cm). At a depth of 10–20 cm, soil moisture content was significantly higher in the control treatment (conventional tillage) than in the simplified tillage system U-4. In this soil layer, compaction significantly increased soil moisture content relative to non-compacted plots. During the flowering of winter oilseed rape, the experimental factors had no significant effect on soil moisture content at both analyzed depths (0–10 cm and 10–20 cm). After harvest, soil moisture content was higher only at a depth of 10–20 cm in compacted plots.

Table 3. Soil moisture content at the analyzed depths in selected growth stages of winter oilseed rape (%).

Treatment	Tillage System				
	Conventional Tillage U-1 (control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
			Date of analysis and measurement depth Beginning of the spring growing season, 0–10 cm		
Not Compacted	*11.80d*	*11.98c*	*12.50b*	*12.83a*	12.28 NS
Artificially Compacted	12.50a	11.43d	12.38b	11.63c	11.99 NS
>Mean	12.50A	11.71B	12.44A	12.23AB	x

Table 3. *Cont.*

Treatment	Tillage System				
	Conventional Tillage U-1 (control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
Beginning of the spring growing season, 10–20 cm					
Not Compacted	*12.68a*	*12.11a*	*11.95ab*	*11.15b*	11.97B
Artificially Compacted	12.45 ns	12.45 ns	12.45 ns	12.70 ns	12.51A
>Mean	12.57A	12.28AB	12.20AB	11.93B	x
Flowering, 0–10 cm					
Not Compacted	*11.27 ns*	*12.88 ns*	*11.82 ns*	*11.76 ns*	11.93 NS
Artificially Compacted	11.64 ns	11.70 ns	11.30 ns	10.97 ns	11.40>NS
>Mean	11.44>NS	12.30>NS	11.56>NS	11.38>NS	x
Flowering, 10–20 cm					
Not Compacted	*12.77c*	*11.50d*	*13.45b*	*13.87a*	12.90 NS
Artificially Compacted	11.23b	11.30b	11.65b	13.83a	12.00 NS
>Mean	12.00 NS	11.40>NS	12.58>NS	13.85 NS	x
After harvest, 0–10 cm					
Not Compacted	*12.85 ns*	*13.0 ns*	*13.06 ns*	*14.43 ns*	13.33 NS
Artificially Compacted	12.70 ns	12.36 ns	12.98 ns	12.12 ns	12.50>NS
>Mean	12.75>NS	12.68 NS	13.04>NS	13.18>NS	x
After harvest, 10–20 cm					
Not Compacted	*13.80 ns*	*12.44 ns*	*12.64 ns*	*12.47 ns*	12.84B
Artificially Compacted	15.70 ns	15.0 ns	16.25 ns	13.99 ns	16.18A
>Mean	14.75>NS	13.72 NS	14.45>NS	12.23>NS	x

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments; ns—not significant.

At the beginning of the spring growing season of winter wheat, soil density at a depth of 0–10 cm was significantly higher in non-compacted plots in all tillage systems (Table 4). At a depth of 10–20 cm, the bulk density of soil was not significantly affected by the experimental factors. In the stem elongation stage, soil density at a depth of 0–10 cm was significantly higher in non-compacted plots, whereas the reverse was noted at a depth of 10–20 cm. In this growth stage, soil density was significantly influenced by the applied tillage treatments. At a depth of 0–10 cm, soil density was significantly highest in tillage systems U-2 (rotary cultivator, pre-sowing plowing, 20 cm) and U-3 (disk cultivator, harrowing, pre-sowing plowing, 20 cm). At a depth of 10–20 cm, soil density was significantly highest in tillage systems U-3 and U-4 (chisel plow, 40 cm, single plowing, 30 cm). The experimental factors significantly influenced soil density after the harvest of winter wheat (Table 4). At both examined depths, soil density was significantly higher in non-compacted plots. In both compacted and non-compacted plots, conventional tillage (control treatment) significantly decreased soil density at a depth of both 0–10 cm and 10–20 cm relative to the remaining tillage systems.

Table 4. Bulk density of soil at the analyzed depths in selected growth stages of winter wheat (g/cm^3).

Treatment	Tillage System				
	Conventional Tillage U-1 (Control)	Simplified Tillage U-2	Simplified Tillage U-3	Simplified Tillage U-4	Mean
Date of analysis and measurement depth					
Beginning of the spring growing season 0–10 cm					
Not Compacted	*1.51 ns*	*1.54 ns*	*1.55 ns*	*1.55 ns*	1.54A
Artificially Compacted	1.55a	1.48b	1.53a	1.50ab	1.52B
Mean	1.53 NS	1.51 NS	1.54 NS	1.53 NS	X
Beginning of the spring growing season, 10–20 cm					
Not Compacted	*1.52 ns*	*1.58 ns*	*1.55 ns*	*1.55 ns*	1.55 NS
Artificially Compacted	1.52 ns	1.55 ns	1.57 ns	1.54 ns	1.55 NS
Mean	1.52 NS	1.57 NS	1.56 NS	1.55 NS	X
Stem elongation, 0–10 cm					
Not Compacted	*1.54b*	*1.60a*	*1.63a*	*1.57b*	1.59A
Artificially Compacted	1.45b	1.50a	1.51a	1.44b	1.48B
Mean	1.50B	1.55A	1.57A	1.51B	X
Stem elongation, 10–20 cm					
Not Compacted	*1.46bc*	*1.43c*	*1.50a*	*1.49b*	1.47B
Artificially Compacted	1.51b	1.55a	1.57a	1.56a	1.55A
Mean	1.49B	1.49B	1.54A	1.53A	X
After harvest, 0–10 cm					
Not Compacted	*1.51b*	*1.54b*	*1.58a*	*1.60a*	1.56A
Artificially Compacted	1.51b	1.53b	1.57a	1.58a	1.55B
Mean	1.51B	1.54A	1.58A	1.59A	X
After harvest, 10–20 cm					
Not Compacted	*1.43c*	*1.52b*	*1.55ab*	*1.57a*	1.52A
Artificially Compacted	1.53a	1.42b	1.54a	1.51a	1.50B
Mean	1.48B	1.47A	1.55A	1.54A	X

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments; ns—not significant.

After the emergence of winter wheat and after harvest, soil moisture content at both depths (0–10 and 10–20 cm) was significantly higher in compacted plots. The reverse was noted in the stem elongation stage (Table 5). Soil moisture content differed significantly between tillage systems, and it was highest in the control treatment (conventional tillage).

After the emergence of spring barley, the experimental factors significantly differentiated the bulk density of soil. At a depth of 0–10 cm, soil density was significantly higher in compacted than in non-compacted plots (Table 6). The analyzed parameter was significantly higher in tillage system U-3 (cultivator, fall plowing, 25–30 cm) than in tillage system U-4 (single plowing, 30 cm) and the control treatment (conventional tillage). In non-compacted plots, soil density was significantly lowest in the simplified tillage system U-4; whereas in compacted plots, the above parameter was significantly higher in tillage systems U-3 and U-4 than in the control treatment and the simplified tillage system U2 (skimming, cultivator, harrowing, fall plowing, 25 cm). The experimental factors (soil compaction, tillage system) did not induce significant differences in soil density at a depth of 10–20 cm. In the stem elongation stage of spring barley and after harvest (Table 6), soil density was significantly higher at both analyzed depths in tillage systems U-3 and U-4 than in the control treatment (conventional tillage) and the simplified tillage system U-2.

Table 5. Soil moisture content at the analyzed depths in selected growth stages of winter wheat (%).

Treatment	Tillage System				
	Conventional Tillage U-1 (Control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
Date of analysis and measurement depth					
Beginning of the spring growing season, 0–10 cm					
Not Compacted	*11.40d*	*11.65c*	*11.95b*	*12.60a*	11.90B
Artificially Compacted	12.43a	11.50c	12.40a	12.08b	12.10A
Mean	11.92C	11.58D	12.18B	12.34A	X
Beginning of the spring growing season, 10–20 cm					
Not Compacted	*12.50a*	*12.12b*	*11.75c*	*11.78c*	12.04B
Artificially Compacted	12.48b	12.45b	12.45b	12.60a	12.50A
Mean	12.49A	12.29B	12.12D	12.19C	X
Stem elongation, 0–10 cm					
Not Compacted	*12.58a*	*12.20c*	*12.49b*	*11.58d*	12.21A
Artificially Compacted	12.63a	12.35b	11.88c	11.65d	12.13B
Mean	12.61A	12.28B	12.19C	11.62D	X
Stem elongation, 10–20 cm					
Not Compacted	*12.58a*	*12.23b*	*12.10c*	*12.05c*	12.24A
Artificially Compacted	11.70c	12.25b	11.65c	12.53a	12.06B
Mean	12.14B	12.24A	11.93C	12.29A	X
After harvest, 0–10 cm					
Not Compacted	*12.58a*	*12.23b*	*12.10c*	*12.05c*	12.24B
Artificially Compacted	12.50c	12.33d	12.61b	12.67a	12.53A
Mean	12.54A	12.28C	12.36B	12.36B	X
After harvest, 10–20 cm					
Not Compacted	*13.20a*	*12.55c*	*12.93b*	*12.43d*	12.78B
Artificially Compacted	13.80a	13.10b	13.18b	12.65c	13.18A
Mean	13.50A	12.83C	13.06B	12.54D	X

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments.

Table 6. Bulk density of soil at the analyzed depths in selected growth stages of spring barley (g/cm^3).

Treatment	Tillage System				
	Conventional Tillage U-1 (Control)	**Simplified Tillage U-2**	**Simplified Tillage U-3**	**Simplified Tillage U-4**	**Mean**
Date of analysis and measurement depth					
Emergence, 0–10 cm					
Not Compacted	*1.46a*	*1.49a*	*1.49a*	*1.42b*	1.47B
Artificially Compacted	1.56ab	1.54b	1.59a	1.58a	1.57A
>Mean	1.51B	1.52AB	1.54A	1.51B	X

Table 6. *Cont.*

Treatment	Tillage System				
	Conventional Tillage U-1 (Control)	Simplified Tillage U-2	Simplified Tillage U-3	Simplified Tillage U-4	Mean
Emergence, 10–20 cm					
Not Compacted	*1.56b*	*1.60a*	*1.56b*	*1.57b*	1.57 NS
Artificially Compacted	1.61a	1.56b	1.59ab	1.57b	1.58 NS
>Mean	1.59 NS	1.58 NS	1.58 NS	1.57 NS	X
Stem elongation, 0–10 cm					
Not Compacted	*1.43b*	*1.57a*	*1.59a*	*1.57a*	1.54A
Artificially Compacted	1.51b	1.45c	1.54a	1.51b	1.50B
>Mean	1.47C	1.51B	1.57A	1.54A	X
Stem elongation, 10–20 cm					
Not Compacted	*1.58a*	*1.49c*	*1.57a*	*1.55b*	1.55B
Artificially Compacted	1.52c	1.59b	1.62a	1.58b	1.58A
>Mean	1.55B	1.54B	1.60A	1.57AB	X
After harvest, 0–10 cm					
Not Compacted	*1.50b*	*1.52b*	*1.60a*	*1.61a*	1.56B
Artificially Compacted	1.58b	1.55b	1.60a	1.61a	1.59A
>Mean	1.54B	1.54B	1.60A	1.61A	X
After harvest, 10–20 cm					
Not Compacted	*1.46b*	*1.54a*	*1.58a*	*1.58a*	1.54 NS
Artificially Compacted	1.57a	1.46b	1.55a	1.55a	1.53 NS
>Mean	1.52B	1.50B	1.57A	1.57A	X

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments; ns—not significant.

After the emergence of spring barley, soil moisture content at a depth of 0–10 cm and 10–20 cm was significantly higher (by approx. 10.1% and 5.2%, respectively) in compacted than in non-compacted plots (Table 7). At a depth of 0–10 cm, the application of a cultivator and fall plowing (tillage system U-3) led to the highest average increase in soil moisture content relative to the control treatment (conventional tillage). In compacted plots, the greatest increase in soil moisture content was observed in the control treatment relative to tillage system U-2 at a depth of 0–10 cm, and relative to tillage system U-4 at a depth of 10–20 cm.

In the stem elongation stage of spring barley, soil moisture content changed under the influence of compaction (Table 7). Soil moisture content was significantly higher in compacted plots at a depth of 0–10 cm, and in non-compacted plots at a depth of 10–20 cm. At both depths (0–10 cm and 10–20 cm), the average soil moisture content was significantly higher in the control treatment (conventional tillage).

Table 7. Soil moisture content at the analyzed depths in selected growth stages of spring barley (%).

Treatment	Tillage System				
	Conventional Tillage U-1 (Control)	Simplified Tillag U-2	Simplified Tillage U-3	Simplified Tillage U-4	Mean
Date of analysis and measurement depth					
Emergence, 0–10 cm					
Not Compacted	*10.90c*	*11.40b*	*11.68a*	*11.35b*	11.33B
Artificially Compacted	12.63a	12.15b	12.53b	12.58b	12.47A
Mean	11.77C	11.78C	12.11A	11.97B	X
Emergence, 10–20 cm					
Not Compacted	*12.73a*	*12.35b*	*12.40b*	*12.03c*	12.38B
Artificially Compacted	13.18a	13.11a	13.18a	12.65b	13.03A
Mean	12.96A	12.73B	12.79B	12.34C	X
Stem elongation, 0–10 cm					
Not Compacted	*11.90b*	*12.16a*	*12.13a*	*12.05a*	12.06B
Artificially Compacted	13.03a	12.50bc	12.58b	12.43c	12.70A
Mean	12.60A	12.33B	12.36B	12.24C	X
Stem elongation, 10–20 cm					
Not Compacted	*13.53a*	*12.80bc*	*12.98b*	*12.75c*	13.02A
Artificially Compacted	12.23c	12.63b	12.28c	12.80a	12.49B
Mean	12.88A	12.72B	12.63C	12.78B	X
After harvest, 0–10 cm					
Not Compacted	*12.85b*	*12.35d*	*13.00a*	*12.65c*	12.71B
Artificially Compacted	13.03a	12.58c	12.73b	13.00a	12.84A
Mean	12.93A	12.47C	12.87B	12.83B	X
After harvest, 10–20 cm					
Not Compacted	*12.85a*	*12.48c*	*12.55b*	*12.35d*	12.56A
Artificially Compacted	12.48b	12.45b	12.48b	12.66a	12.50B
Mean	12.67A	12.47C	12.52B	12.48B	X

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments.

After the harvest of spring barley, the experimental factors significantly affected soil moisture content (Table 7). At a depth of 0–10 cm, soil moisture content was higher (12.8%) in compacted plots, whereas the reverse was noted at a depth of 10–20 cm. In non-compacted plots, soil moisture content at a depth of 0–10 cm was highest (13.0%) in tillage system U-3 (cultivator, fall plowing, 25–30 cm). In compacted plots, the greatest increase in the analyzed parameter was observed after conventional tillage (control treatment) and single plowing in the fall (tillage system U-4). At a depth of 10–20 cm, soil moisture content was significantly higher in tillage systems U-1 (non-compacted plots) and U-4 (compacted plots).

Soil compaction had a significant effect on the seed yield of winter oilseed rape (Table 8), which was significantly higher (by 10.3%) in compacted than in non-compacted plots.

Table 8. Yields of winter oilseed rape, winter wheat and spring barley (t·ha^{-1}).

Soil Compaction	Tillage System				
	Conventional Tillage U-1 (Control)	**Simplified Tillage U-2**	**Simplified TillageU-3**	**Simplified TillageU-4**	**Mean**
		Winter oilseed rape			
Not Compacted	*3.20b*	*3.47a*	*2.19d*	*3.53a*	3.10B
Artificially Compacted	3.62a	3.57a	2.85c	3.60a	3.42A
Mean	3.41B	3.53AB	2.52C	3.57A	X
		Winter wheat			
Not Compacted	*7.90b*	*8.00ab*	*7.70bc*	*6.80d*	7.60B
Artificially Compacted	8.20a	7.90b	8.00ab	7.60c	7.93A
Mean	8.05A	7.95AB	7.85B	7.20C	X
		Spring barley			
Not Compacted	*5.20a*	*5.30a*	*5.00b*	*4.90c*	5.10A
Artificially Compacted	4.60c	5.10ab	4.70c	4.50c	4.72B
Mean	4.90B	5.20A	4.85B	4.70C	X

Uppercase letters denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an evaluation of the main effects; lowercase letters in italics denote homogeneous groups in Tukey's HSD test ($p < 0.05$) for non-compacted treatments; lowercase letters in plain typeface denote homogeneous groups in Tukey's HSD test ($p < 0.05$) in an analysis of the interactions between the experimental factors in compacted treatments.

In compacted and non-compacted treatments, the yield of winter oilseed rape was lowest in tillage system U-3 (skimming and harrowing after harvest, without pre-sowing plowing). In non-compacted plots, the seed yield of winter oilseed rape in tillage system U-4 (single plowing) was 10% higher (3.53 t·ha^{-1}) than in the control treatment (conventional tillage) and nearly 38% higher than in the simplified tillage system U-2 (skimming 10 cm, harrowing). In compacted plots, the seed yield of winter oilseed rape was significantly lowest in tillage system U-3 (skimming and harrowing after harvest, without pre-sowing plowing), 21.3% lower than in the control treatment (conventional tillage). Cereal grain yields were significantly influenced by the experimental factors (Table 8). The grain yield of winter wheat ranged from 6.80 to 8.20 t·ha^{-1}, and it was significantly higher (by 4.3%) in compacted than in non-compacted plots. The reverse was observed in spring barley, where grain yield was significantly lower (by 7.5%) in compacted plots than in non-compacted plots. The greatest decrease in wheat yield (by approx. 10.6%) was noted in tillage system U-4 (chisel plow, single plowing), compared with the control treatment (conventional tillage). In the cultivation of spring barley, the absence of post-harvest cultivation and the application of a single plowing treatment (U-4) significantly decreased grain yield (by 9.6%) relative to tillage system U-2. In non-compacted and compacted plots, barley grain yields were higher in tillage system U-2 (5.30 and 5.10 t·ha^{-1}, respectively). In non-compacted plots, winter wheat yields were higher in tillage system U-2, whereas in compacted plots, winter wheat yields increased after conventional tillage (control treatment). In non-compacted and compacted plots, winter wheat yields were 14.0% and 7.3% lower (6.80 and 7.60 t·ha^{-1}, respectively) in tillage system U-4 (chisel plow, single plowing) than in the control treatment (conventional tillage).

4. Discussion

Conventional tillage delivers unquestioned benefits, but it also exerts a negative impact on the physical properties of soil. According to Shah et al. [16], intensive tillage leads to soil compaction which decreases plant growth, influences various physiological processes in soil and, consequently, compromises the productive capacity of soil. Conventional tillage increases soil porosity and decreases the bulk density of soil in early stages of plant growth. In successive growth stages, soil porosity decreases due to compaction, and its bulk density increases [25]. In the present study, soil compaction and the evaluated tillage methods exerted varied effects on the bulk density of soil in different stages of plant development and in different soil horizons. Crops respond differently to soil compaction depending upon their rooting system. According to Reichert at al. [21] an increase in the bulk density is not necessarily detrimental to crop growth, because at certain limits this increase may contribute to soil water storage. This means that are the limits of soil bulk density acceptable for adequate crop growth and yield.

In our study in the cultivation of winter oilseed rape, the bulk density of soil changed during the growing season. The bulk density of soil at a depth of 0–10 cm (non-compacted plots) decreased after chisel plowing and pre-sowing plowing (20 cm). During flowering (compacted plots), the analyzed parameter was significantly lower at a depth of 0–10 cm and significantly higher at a depth of 10–20 cm. At the beginning of the spring growing season of winter wheat (compacted plots), the application of a rotary cultivator and pre-sowing plowing (20 cm) increased the bulk density of soil relative to conventionally tilled plots. In the stem elongation stage, the bulk density of soil was also higher in compacted plots at a depth of 0–10 cm, whereas the reverse was noted at a depth of 10–20 cm. After spring barley emergence (compacted plots), the bulk density of soil at a depth of 0–10 cm was highest after cultivation and fall plowing (25–30 cm) (tillage system U-3); whereas at a depth of 10–20 cm, the analyzed parameter was highest after plowing. In the stem elongation stage (compacted plots), the bulk density of soil in the 10–20 cm horizon was significantly higher in tillage system U-3 than in system U-1 (conventional tillage). The results of the present study are partially consistent with the findings of other authors. Czyż and Dexter [26] observed that soil density increased with the depth of the analyzed layers. In their study, the bulk density of soil ranged from 1.13 to 1.59 $Mg \cdot m^{-3}$, where the lowest values were observed in after conventional tillage, and higher values were noted in simplified tillage systems. In a study by Majchrzak et al. [27], the bulk density of soil differed considerably across sampling dates and soil horizons. The cited authors also demonstrated that simplified tillage induced a greater increase in the bulk density of soil at a depth of 2–8 cm and 13–18 cm than at a depth of 28–33 cm in comparison with conventional tillage. According to Gűlser et al. [28], the bulk density of soil was higher in all conventionally tilled plots than in plots subjected to simplified tillage. Grant and Lafond [29] found that the bulk density of loamy soil in the 0–15 cm horizon was lower after simplified tillage (0.90–1.29 cm^2) than after conventional tillage (0.99–1.33 cm^2). In other studies, the evaluated parameter increased by 0.11 and 0.05 $g \cdot cm^{-3}$ at a depth of 0–5 cm and 5–10 cm, respectively, after simplified tillage relative to conventional tillage, whereas no significant changes were noted in deeper horizons [30–34] reported an increase in the bulk density of soil after simplified tillage in comparison with conventional tillage. The bulk density of soil decreases with an increase in its organic matter content which, in turn, is determined by the rotated crops. There is considerable evidence to indicate that organic matter content negatively correlated with the bulk density of soil and positively correlated with total soil porosity [35,36].

Moisture content is the key determinant of soil susceptibility to compaction due to increased resistivity and decreased water potential [2]. In the present study, compaction increased soil moisture content in the cultivation of winter wheat and spring barley, but not winter oilseed rape. According to a review article by Shah et al. [16], the moisture content of soil increases due to a reduction in total soil porosity. Compaction decreases pore space, which inhibits water movement in the soil profile and prevents water from reaching deeper horizons [16,37].

In the current experiment, soil moisture content varied across the compared tillage systems and measurement dates. Gate et al. [38] and Stanek-Tarkowska et al. [30] demonstrated that in contrast to conventional tillage, simplified tillage increased the moisture content of soil. Less disturbed soil is characterized by lower aeration and higher organic matter content [2], which increases the content of organic carbon in the long-term perspective [1].

In the present study, skimming and harrowing at the beginning of the spring growing season of oilseed rape and the absence of pre-sowing plowing increased soil moisture content which was significantly higher in the 10–20 cm horizon in compacted plots. Chisel plowing and single plowing had the opposite effect. After the emergence of winter wheat, soil moisture content at a depth of 0–10 cm and 10–20 cm was higher in compacted than in non-compacted plots. Soil moisture content at a depth of 10–20 cm was highest after conventional tillage in non-compacted plots and after chisel plowing and single plowing in compacted plots. In the stem elongation stage (non-compacted plots), soil moisture content was significantly reduced in both soil horizons (0–10 cm and 10–20 cm) after chisel plowing and single plowing (tillage system U-4). After the emergence of spring barley, conventional tillage (compacted plots) increased soil moisture content at a depth of 0–10 cm relative to skimming, cultivation and fall plowing (25 cm) (tillage system U-2), and at a depth of 10–20 cm relative to single plowing (30 cm) (tillage system U-4). In the stem elongation stage, conventional tillage significantly increased soil moisture content in both horizons in both compacted and non-compacted plots.

Małecka et al. [15] reported that the moisture content of soil at a depth of 0–10 cm and 10–20 cm increased significantly when a stubble cultivator was used instead of a conventional plow. According to many authors, the replacement of conventional tillage with plowless tillage increased moisture content and decreased the capillary water capacity of topsoil [39–42]. The cited authors observed that higher soil moisture content is particularly desirable in dry years because it counteracts the adverse consequences of drought. Long-term experiments have demonstrated that prolonged plowless tillage significantly improves the physical properties of soil by promoting the growth of soil fauna and the formation of biogenic pores, in particular pores with a vertical orientation [40,43,44]. According to Dexter [37], compaction inhibits air and water transport in the soil profile and reduces water retention. Tillage system exerts a marked influence on pore size distribution because heavy agricultural machinery with high axle load decreases pore size and pore volume in conventional tillage systems. In conventional tillage systems, the number of macropores increases at the beginning of the growing season, but pore size is reduced in successive stages of plant growth due to soil compaction. Pore structure is considerably affected by time, tillage intensity and weather conditions, in particular rainfall [45]. Dexter [46] defined soil compaction as a process that alters the distribution, size and shape of pores in the soil profile. Boizard et al. [47] investigated the influence of repeated wheeling on pore size distribution and volume and did not observe visible macropores in highly compacted soil. A morphological analysis revealed platy soil structures in the upper part of the highly compacted zones under the tilled layers, with cracks penetrating deeper into the soil. According to Koch et al. [48], compaction exerts adverse effects on the size of macropores and the permeability of topsoil (0.05–0.1 m and 0.18–0.23 cm) and subsoil (0.4–0.45 m).

Despite extensive research, the effect of simplified tillage on crop yields has not been fully elucidated to date. Some authors reported similar yields in simplified and conventional tillage systems [49,50], while others reported lower [30,51] or higher yields in simplified than in conventional tillage systems [1]. In the current study, winter oilseed rape yields were significantly higher in compacted plots, and the greatest decrease in yields was noted in tillage system U-3 (skimming and no pre-sowing plowing) regardless of soil compaction. Chisel plowing and single plowing (tillage system U-4) induced the greatest decrease in wheat yields relative to conventional tillage. Single plowing (tillage system U-4) decreased spring barley yields relative to tillage system U-2 (skimming, fall plowing, 25 cm). Małecka et al. [15] reported that single plowing significantly (by approx. 10%) decreased winter wheat yields in comparison with conventional tillage, and that winter wheat yields were higher after the application of a disc harrow than a rotary cultivator. In a study by Budzyński et al. [52], shallow tillage (10 cm) reduced oilseed rape yields by only 4% relative to deep tillage (22 cm), whereas in a study by Jankowski [53], oilseed rape yields decreased by 10% after shallow tillage (10 cm) in comparison with moderately deep tillage.

Somewhat different results were reported by Sieling and Christien [54], where oilseed rape yields were lower after disk harrowing, compared with conventional tillage. Wesołowski and Cierpiała [55] observed that single plowing before sowing decreased wheat yields by around 4.5%, whereas single plowing combined with soil compaction before sowing increased yields in comparison with conventional tillage. Małecka et al. [15] reported that single plowing and shallow tillage had no significant effect on spring barley yields or even increased yields by 5–10%, whereas the application of a stubble cultivator and a disk harrow decreased barley yields.

5. Conclusions

In the present study, soil compaction and simplified tillage exerted varied effects on the bulk density of soil, soil moisture content or crop yields. The changes in the bulk density and moisture content of soil varied across crop species, the developmental stages of plants, and soil horizons. In the cultivation of winter oilseed rape, compaction and simplified tillage did not induce significant changes in the bulk density or moisture content of soil. In plots sown with winter wheat and spring barley, significant differences in the bulk density of soil were observed at a depth of 0–10 cm. In this soil horizon, the bulk density of soil decreased in wheat cultivation and increased in barley cultivation in response to pre-sowing compaction. In the cultivation of winter wheat and spring barley, compaction increased soil moisture content in both soil horizons (0–10 cm and 10–20 cm). In these cereal species (in particular in compacted plots sown with barley), soil moisture content was higher after conventional tillage (tillage system U-1). Oilseed rape and wheat yields were higher in compacted plots, whereas barley yields were higher in non-compacted plots. Oilseed rape yields were highest in simplified tillage systems U-2 (chisel plowing) and U-4 (without skimming); winter wheat yields were highest in system U-1 (conventional tillage); and spring barley yields were highest in system U-2 (chisel plowing). Soil compaction combined with simplified tillage decreased oilseed rape yields, and disc harrowing after harvest compromised wheat yields (tillage system U-3). Soil compaction decreased barley yields in tillage systems U-1, U-3 and U-4.

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References

1. De Cárcer, P.S.; Sinaj, S.; Santonja, M.; Fossati, D.; Jeangros, B. Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties. *Soil Tillage Res.* **2019**, *190*, 209–219. [CrossRef]
2. Dekemati, I.; Simon, B.; Vinogradov, S.; Birkás, M. The effects of various tillage treatments on soil physical properties, earthworm abundance and crop yield in Hungary. *Soil Tillage Res.* **2019**, *194*, 104334. [CrossRef]

3. Romaneckas, K.; Šarauskis, E.; Pilipavičius, V.; Sakalauskas, A. Impact of short-term ploughless tillage on soil physical properties, winter oilseed rape seedbed formation and productivity parameters. *J. Food Agric. Environ.* **2011**, *9*, 295–299.
4. Tarawally, M.A.; Medina, H.; Frómeta, M.E.; Itza, C.A. Field compaction at different soil-water status: Effects on pore size distribution and soil water characteristics of a Rhodic Ferralsol in Western Cuba. *Soil Tillage Res.* **2004**, *76*, 95–103. [CrossRef]
5. Woźniak, A. Effect of various systems of tillage on winter barley yield, weed infestation and soil properties. *Appl. Ecol. Environ. Res.* **2020**, *18*, 3483–3496. [CrossRef]
6. Schlüter, S.; Großmann, C.; Diel, J.; Wu, G.M.; Tischer, S.; Deubel, A.; Rücknagel, J. Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties. *Geoderma* **2018**, *332*, 10–19. [CrossRef]
7. Voltr, V.; Wollnerová, J.; Fuksa, P.; Hruška, M. Influence of Tillage on the Production Inputs, Outputs, Soil Compaction and GHG Emissions. *Agriculture* **2021**, *11*, 456. [CrossRef]
8. Aikins, S.; Afuakwa, J. Effect of four different tillage practices on soil physical properties under cowpea. *Agric. Biol. J. N. Am.* **2012**, *3*, 17–24. [CrossRef]
9. Augustin, K.; Kuhwald, M.; Brunotte, J.; Duttmann, R. Wheel load and wheel pass frequency as indicators for soil compaction risk: A four-year analysis of traffic intensity at field scale. *Geosciences* **2020**, *10*, 292. [CrossRef]
10. Somasundaram, J.; Chaudhary, R.S.; Awanish Kumar, D.; Biswas, A.K.; Sinha, N.K.; Mohanty, M.; Hati, K.M.; Jha, P.; Sankar, M.; Patra, A.K.; et al. Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols. *Eur. J. Soil Sci.* **2018**, *69*, 879–891. [CrossRef]
11. Byszewski, W.; Haman, J. The effect of mechanization on the soil environment. In *Gleba, Maszyna, Roślina (Soil, Machine, Crop)*; PWN: Warszawa, Poland, 1974; pp. 59–142.
12. Ernst, G.; Emmerling, C. Impact of five different tillage systems on soil organic carbon content and the density, biomass, and community composition of earthworms after a ten year period. *Eur. J. Soil Biol.* **2009**, *45*, 247–251. [CrossRef]
13. Moinfar, A.; Shahgholi, G.; Abbaspour-Gilandeh, Y.; Herrera-Miranda, I.; Hernández-Hernández, J.L.; Herrera-Miranda, M.A. Investigating the Effect of the Tractor Drive System Type on Soil Behavior under Tractor Tires. *Agronomy* **2021**, *11*, 696. [CrossRef]
14. Derpsch, R.; Friedrich, T. Development and Current Status of No-till Adoption in the World. In Proceedings of the 18th Triennial Conference of the International Soil Tillage Research Organization (ISTRO), Proceedings on CD, Izmir, Turkey, 15–19 June 2009; pp. 1–13.
15. Małecka, I.; Blecharczyk, A.; Sawinska, Z.; Piechota, T.; Waniorek, B. Cereals yield response to tillage methods. *Fragm. Agron.* **2012**, *29*, 114–123. (In Polish)
16. Shah, A.N.; Tanveer, M.; Shahzad, B.; Yang, G.; Fahad, S.; Ali, S.; Bukhari, M.A.; Tung, S.A.; Hafeez, A.; Souliyanonh, B. Soil compaction effects on soil health and cropproductivity: An overview. *Environ. Sci. Pollut. Res.* **2017**, *24*, 10056–10067. [CrossRef]
17. Botta, G.F.; Tolón-Becerra, A.; Bienvenido, F.; Rivero, D.; Laureda, D.A.; Ezquerra-Canalejo, A.; Contessotto, E.E. Sunflower (Helianthus annuus L.) harvest: Tractor and grain chaser traffic effects on soil compaction and crop yields. *Land Degrad. Dev.* **2018**, *29*, 4252–4261. [CrossRef]
18. Orzech, K.; Załuski, D. Effect of companion crops and crop rotation systems on some chemical properties of soil. *J. Elem.* **2020**, *25*, 931–949. [CrossRef]
19. Wang, Z.; Li, Y.; Li, T.; Zhao, D.; Liao, Y. Tillage practices with different soil disturbance shape the rhizosphere bacterial community throughout crop growth. *Soil Tillage Res.* **2020**, *197*, 104501. [CrossRef]
20. Horn, R.; Vossbrink, J.; Becker, S. Modern forestry vehicles and their impacts on soil physical properties. *Soil Tillage Res.* **2004**, *79*, 207–219. [CrossRef]
21. Reichert, J.M.; Suzuki, L.E.A.S.; Reinert, D.J.; Horn, R.; Håkansson, I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil Tillage Res.* **2009**, *102*, 242–254. [CrossRef]
22. Van Eerd, L.L.; Congreves, K.A.; Hayes, A.; Verhallen, A.; Hooker, D.C. Long-term tillage and crop rotation effects on soil quality, organic carbon, and total nitrogen. *Can. J. Soil Sci.* **2014**, *94*, 303–315. [CrossRef]
23. FAO; IUSS. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps—Update 2015. In *World Reference Base for Soil Resources 2014. World Soil Resources Reports No. 106*; FAO: Rome, Italy, 2015; p. 203, ISBN 9789251083697.
24. TIBCO Software Inc. Statistica (Data Analysis Software System), Version 13. Available online: http://www.tibco.com.2017 (accessed on 13 July 2021).
25. Güclü Yavuzcan, H. Wheel traffic impact on soil conditions as influenced by tillage system in Central Anatolia. *Soil Tillage Res.* **2000**, *54*, 129–138. [CrossRef]
26. Czyż, E.A.; Dexter, A.R. Soil physical properties as affected by traditional, reduced and no-tillage for winter wheat. *Int. Agrophys.* **2009**, *23*, 319–326.
27. Majchrzak, L.; Skrzypczak, G.; Piechota, T. No TitleImpact of simplified soil tillage under maize on soil physical properties. *Fragm. Agron.* **2004**, *3*, 107–119. (In Polish)
28. Gülser, F.; Salem, S.; Gülser, C. Changes in some soil properties of wheat fields under conventional and reduced tillage systems in Northern Iraq. *Eurasian J. Soil Sci.* **2020**, *9*, 314–320. [CrossRef]
29. Grant, C.A.; Lafond, G.P. The effects of tillage systems and crop sequences on soil bulk density and penetration resistance on a clay soil in southern Saskatchewan. *Can. J. Soil Sci.* **1993**, *73*, 223–232. [CrossRef]
30. Stanek-Tarkowska, J.; Czyż, E.A.; Dexter, A.R.; Sławiński, C. Effects of reduced and traditional tillage on soil properties and diversity of diatoms under winter wheat. *Int. Agrophys.* **2018**, *32*, 403–409. [CrossRef]

31. Fabrizzi, K.P.; García, F.O.; Costa, J.L.; Picone, L.I. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. *Soil Tillage Res.* **2005**, *81*, 57–69. [CrossRef]
32. McVay, K.A.; Budde, J.A.; Fabrizzi, K.; Mikha, M.M.; Rice, C.W.; Schlegel, A.J.; Peterson, D.E.; Sweeney, D.W.; Thompson, C. Management Effects on Soil Physical Properties in Long-Term Tillage Studies in Kansas. *Soil Sci. Soc. Am. J.* **2006**, *70*, 434–438. [CrossRef]
33. Mühlbachová, G.; Kusá, H.; Růžek, P. Soil characteristics and crop yields under differenttillage techniques. *Plant Soil Environ.* **2015**, *61*, 566–572. [CrossRef]
34. Gajda, A.M.; Czyz, E.A.; Dexter, A.R.; Furtak, K.M.; Grządziel, J.; Stanek-Tarkowska, J. Effects of different soil management practices on soil properties and microbial diversity. *Int. Agrophys.* **2018**, *32*, 81–91. [CrossRef]
35. Candemir, F.; Gülser, C. Effects of different agricultural wastes on some soil quality indexes in clay and loamy sand fields. *Commun. Soil Sci. Plant Anal.* **2011**, *42*, 13–28. [CrossRef]
36. Demir, Z.; Gülser, C. Effects of rice husk compost application on soil quality parameters in greenhouse conditions. *Eurasian J. Soil Sci.* **2015**, *4*, 185–190. [CrossRef]
37. Dexter, A.R. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* **2004**, *120*, 201–214. [CrossRef]
38. Gate, O.P.; Czyż, E.; Dexter, A.R. Soil physical quality, as a basis for relationships between some key physical properties of arable soils. In *Soil Management for Sustainability*; Horn, R., Fleige, H., Peth, S., Peng, X., Eds.; Schweizerbart Science Publishers: Stuttgart, Germany, 2006; pp. 102–109, ISBN 9783510653768.
39. Boydaş, M.G.; Turgut, N. Effect of tillage implements and operating speeds on soil physical properties and wheat emergence. *Turk. J. Agric. For.* **2007**, *31*, 399–412.
40. Morris, N.L.; Miller, P.C.H.; Orson, J.H.; Froud-Williams, R.J. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. *Soil Tillage Res.* **2010**, *108*, 1–15. [CrossRef]
41. Raczkowski, C.W.; Mueller, J.P.; Busscher, W.J.; Bell, M.C.; McGraw, M.L. Soil physical properties of agricultural systems in a large-scale study. *Soil Tillage Res.* **2012**, *119*, 50–59. [CrossRef]
42. Rahman, M.H.; Okubo, A.; Sugiyama, S.; Mayland, H.F. Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. *Soil Tillage Res.* **2008**, *101*, 10–19. [CrossRef]
43. Anken, T.; Weisskopf, P.; Zihlmann, U.; Forrer, H.; Jansa, J.; Perhacova, K. Long-term tillage system effects under moist cool conditions in Switzerland. *Soil Tillage Res.* **2004**, *78*, 171–183. [CrossRef]
44. Holland, J.M. The environmental consequences of adopting conservation tillage in Europe: Reviewing the evidence. *Agric. Ecosyst. Environ.* **2004**, *103*, 1–25. [CrossRef]
45. Karunatilake, U.P.; Van Es, H.M. Rainfall and tillage effects on soil structure after alfalfa conversion to maize on a clay loam soil in New York. *Soil Tillage Res.* **2002**, *67*, 135–146. [CrossRef]
46. Dexter, A.R. Advances in characterization of soil structure. *Soil Tillage Res.* **1988**, *11*, 199–238. [CrossRef]
47. Boizard, H.; Yoon, S.W.; Leonard, J.; Lheureux, S.; Cousin, I.; Roger-Estrade, J.; Richard, G. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. *Soil Tillage Res.* **2013**, *127*, 34–44. [CrossRef]
48. Koch, H.J.; Heuer, H.; Tomanová, O.; Märländer, B. Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. *Soil Tillage Res.* **2008**, *101*, 69–77. [CrossRef]
49. Büchi, L.; Wendling, M.; Amossé, C.; Jeangros, B.; Sinaj, S.; Charles, R. Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland. *Soil Tillage Res.* **2017**, *174*, 120–129. [CrossRef]
50. Pittelkow, C.M.; Linquist, B.A.; Lundy, M.E.; Liang, X.; van Groenigen, K.J.; Lee, J.; van Gestel, N.; Six, J.; Venterea, R.T.; van Kessel, C. When does no-till yield more? A global meta-analysis. *F. Crop. Res.* **2015**, *183*, 156–168. [CrossRef]
51. Alvarez, R.; Steinbach, H.S. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil Tillage Res.* **2009**, *104*, 1–15. [CrossRef]
52. Budzyński, W.; Jankowski, K.J.; Szczebiot, M. Effects of simplifying soil tillage and weed control on yielding and production cost of winter rapeseed I. Winterhardiness, weed infestation and yield of winter rapeseed. *Rośliny Oleiste Oilseed Crop.* **2000**, *21*, 487–502. (In Polish)
53. Jankowski, K.J. Effect of the depth of plouging on the economic efficiency of production of winter rape oilseeds. *Fragm. Agron.* **2002**, *19*, 273–284. (In Polish)
54. Sieling, K.; Christen, O. Yield, N uptake and N leaching after rapeseed grown in different crop management systems in Northern Germany. In Proceedings of the 10th International Rapeseed Congress, Canberra, Ausatrilia, 26–29 September 1999.
55. Wesołowski, M.; Cierpiała, R. Yield of winter wheat depending on pre sowing tillage metod. *Fragm. Agron.* **2011**, *28*, 106–118. (In Polish)