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RESEARCH

Influence of soil tillage system on soil compaction and winter wheat yield

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ABSTRACT

Tillage systems can affect soil compaction, water content, soil temperature, and yields of cultivated plants. This work examined a Vertisol and the influence of the tillage system on soil compaction and yield of winter wheat (*Triticum aestivum* L.) grains. The trial was conducted in the vicinity of Požega, Western Serbia, from 2014 to 2017. Four tillage systems (conventional tillage, reduced tillage, disc harrowing, and no-tillage) were applied in the experiment. Tillage systems have significantly influenced soil compaction, measurement time, and soil depth. Mean soil compaction in 2016-2017 was 1.96 MPa, which was 0.17 MPa lower than in 2014-2015 and 0.30 MPa higher than in 2015-2016. The highest mean wheat yield occurred in the conventional tillage system (4033 kg ha^{-1}), and it was significantly higher than the yield obtained in other soil tillage systems. There was a strong negative correlation between mean wheat yield and soil compaction. It was necessary to apply complete soil tillage to achieve satisfactory wheat grain yields on the Vertisol, which implies plowing and adequate pre-sowing soil preparation.

Key words: Conventional tillage, no-tillage, reduced tillage, *Triticum aestivum*.

INTRODUCTION

Tillage systems can affect soil filtration, water content, and soil temperature; they can significantly modify the physical, chemical, and biological properties of the soil. Küstermann et al. (2013) examined the effects of a conventional and reduced treatment with different N rates on wheat (*Triticum aestivum* L.) yield in a crop rotation with potatoes; they collected data that indicated that conventional tillage (CT) at low and medium N rates produced higher wheat yields than (RT). These significantly higher wheat yields achieved in the CT system compared with RT are reported by Shahzad et al. (2016).

Moraru and Rusu (2012) examined the influence of CT, RT, and sowing with no-tillage (NT) and suggest that differences in wheat yield with these systems are nonsignificant. Khorami et al. (2018) examined the effects of CT and RT and sowing with NT on several wheat genotypes and concluded that the highest yields were achieved in the RT system, followed by the CT system, while the lowest yields occurred in the NT system.

There are contradictory data on crop yields in the RT and CT systems. Claassen (2012) considers that tillage with no plowing reduced erosion by more than one-third of arable land in the USA. Pittelkow et al. (2015) point out that the tillage systems must be adequately assessed economically and ecologically and indicate that NT systems in the dry regions of Africa increase yields compared with CT.

Analyzing the effect of CT and the NT system with wheat straw mulching on the yield of winter wheat in the dry regions of north-western China, Huang et al. (2012) mention that the NT system with wheat straw mulch increased mean wheat yield by 15.6% to 16.8% compared with CT. Copec et al. (2015) studied the influence of soil tillage systems on soil water content and yields of wheat and maize and concluded that the highest yield was achieved in the direct sowing system, which also had the highest water content. They point out that soil water content is positively correlated with wheat yield and is one of the decisive factors of plant production. In addition, Acar et al. (2017) studied similar problems under Mediterranean climate conditions and indicated that the differences in wheat grain yields among tillage systems were not significant, while the highest soil water content was achieved in conservation tillage and NT systems.

Soil compaction is one of the main forms of degradation. Mueller et al. (2010) state that compaction is a physical form of soil degradation that changes the soil structure and results in lower soil productivity. Pansak et al. (2008) and Govaerts et al. (2009) indicate that conventional soil cultivation best preserves soil moisture because crop residues are retained in the soil, evaporation is lower, and infiltration is higher.

Botta et al. (2010) point out that plant yields are reduced after several years of applying the NT system. This could be due to gradual soil compaction as a result of passages with heavy tractor seeders and harvesters, especially if these operations are carried out on moist soil.

Martinez et al. (2011) examined the impact of NT systems, NT systems and their procedures, and CT on soil compaction and wheat yield, and they conclude that the NT system combined with chisel plowing showed less soil compaction, especially at depths greater than 10 cm compared with other processing systems. The highest compaction was recorded in the NT system.

Hartmann et al. (2012) point out that droughts, as well as extreme highly intense rainfall, are important risk factors for soil compaction. Sang et al. (2016) indicate that long-term RT results in the formation of a watertight layer that prevents the infiltration of precipitation, which in turn results in lower wheat growth and lower yields. Barut and Celik (2017) showed that soil compaction in the CT system was 1.26 to 1.32 g cm^{-3} at all depths and was lower than in conservation tillage and sowing with NT. Organic matter content, water content, texture, and structure are the four essential factors determining the degree of soil compaction. Soil compaction has a direct effect on these factors which can impair physical and mechanical soil properties and create unfavorable conditions for plant growth and development (Nawaz et al., 2013).

Overall, soil compaction leads to a slowdown in the absorption of water and nutrients, weaker development of the root system as to length and penetration into the deeper layers, slow plant growth, which result in weaker plant growth and yield reduction (Nosalewicz and Lipiec, 2014; Prakash et al., 2014; D'Or and Destain, 2016). Therefore, the aim was to examine a Vertisol and the influence of tillage systems on soil compaction and yield of winter wheat grains.

MATERIALS AND METHODS

Description of study areas

The trial was conducted in the vicinity of Pozega, Western Serbia, during 2014-2015, 2015-2016, and 2016-2017 on a Vertisol. Pozega is located in southwest Serbia (43°50'28" N, 20°02'17" E; 310 to 900 m.a.s.l.)

Treatments and experimental design

The experiment included the four soil tillage systems of conventional tillage (CT): autumn plowing + disc-harrowing + seedbed preparation, reduced tillage (RT): disc harrowing + seedbed preparation, disc harrowing (RT1), and no-tillage (NT). The wheat (*Triticum aestivum* L.) 'Pobeda' was planted. The trial design was the block system with four replicates. Sowing in each season was carried out at the end of October. Since wheat was cultivated in a crop rotation with maize (*Zea mays* L.), the harvest residues were removed immediately after the maize harvest. In the CT variant, basic tillage was conducted with a plow at a 25 cm depth, and the pre-sowing preparation was done at the 15 cm soil depth. In the RT treatment, disc harrowing was applied to a 15 cm depth, followed by pre-sowing seedbed preparation. In the RT1 treatment, soil was prepared with a disc harrow at a 15 cm depth. Before sowing to control weeds and make sowing easier in the NT treatment, 3 L ha^{-1} total herbicide glyphosate (2-[phosphonomethylamino] acetic acid; Glifosav 480, Chemical Agrosava, Belgrade, Serbia) was used. Mineral nutrition involved applying 300 kg ha^{-1} NPK fertilizer (15:15:15) before sowing and 200 kg ha^{-1} calcium ammonium nitrate (CAN) fertilizer for all varieties. Weed treatment was carried out in April with the herbicide metsulfuron-methyl (methyl 2-[{4-methoxy-6-methyl-1,3,5-triazin-2-yl}carbamoylsulfamoyl] benzoate; Metmark WP, Agromarket, Belgrade, Serbia) at 0.01%.

Plot size to measure soil compaction was 70 m^2 with four replicates. Mean moisture content was also measured. Compaction was measured after sowing (AS) and before harvesting (BH) of wheat to a 40 cm depth with the Penetrologger Eijkelkamp, version 6.0 software (Eijkelkamp, Giesbeek, Netherlands). Compaction was measured according to the NEN 5140 standard (Royal Netherlands Standardization Institute, Delft, Netherlands), 2 cm s^{-1} penetration rate with a deviation of no more than 0.5 cm s^{-1}, and all according to the standard soil cone penetrometer (ASAE S313.3; ASAE Standards, 2002). Compaction results were graphically illustrated for each year. Harvest occurred at full maturity in the first half of July.

Statistical analysis

Yield was calculated in each plot and adjusted to 14% grain moisture content. The dependence between yield and soil compaction was determined by Pearson's correlation coefficient. Results were processed statistically by ANOVA using the WASP, version 1.0 software (Indian Council of Agricultural Research [ICAR]-Central Coastal Agricultural Research Institute [CCARI], Ela, Goa, India). Individual comparisons were determined by the LSD test.

Soil and climatic conditions

Tables 1 and 2 show the soil chemical properties and the climatic characteristics of the area, respectively. The hydrolytic acidity of the soil was determined by Ca acetate extraction by Kappen's method. Humus was determined by the Kotzman method, total N by the Kjeldahl method, and available P and K by the Egner-Riehm (A-L) method.

The pH value of the soil solution for KCl in the 0-30 cm layer was 5.80; this soil belongs to a group of moderately acidic soils. According to the humus content (3.1%), this soil belongs to a group of well-supplied soil. The N content (0.15%) is within the limits of a good supply, while the P content (10.7 mg 100 g^{-1}) in this soil is between a low and medium supply. According to the K content (20 mg 100 g^{-1}), this soil belongs to a group of an ideally supplied soil. In this type of soil, with proper agrotechnical and pedomeliorative measures (liming), plant production can be very successful.

This soil belongs to the class of clay soils that are suitable for cultivation for a short period of time and have a heavy texture (Golubovic et al., 2011). Full tillage is required on such soils to create a favorable water-air regime for plant growth and thus obtain higher yields.

Table 1. Soil chemical properties.

				Available nutrients		
Depth	pH		Humus	N	P_2O_5	K_2O
cm	H_2O	KCl	%	%	— mg 100 g^{-1} —	
0-30	7.2	5.80	3.1	0.15	10.7	20.0

Table 2. Climatic conditions in Požega, Western Serbia, from 2014 to 2017.

	Precipitation				Mean air temperature			
Month	2014	2015	2016	2017	2014	2015	2016	2017
	mm				°C			
January		39.2	60.6	20.6		0.1	-1.2	-6.6
February		55.6	30.4	30.9		1.9	6.6	2.9
March		74.5	168.6	35.9		5.4	6.5	8.3
April		52.1	46.6	76.7		10.0	12.3	9.4
May		75.0	145.5	76.8		16.6	14.2	15.3
June		131.3	75.8	84.2		18.2	19.9	20.4
July		11.1	72.4	55.9		22.4	21.1	21.5
August		39.5	180.2	43.3		21.6	18.7	21.0
September		66.2	43.8	41.7		17.6	15.7	15.7
October	54.9	65.8	81.0	108.1	11.3	11.0	9.7	10.1
November	33.7	43.8	85.9	29.8	6.6	4.8	4.6	4.5
December	89.4	5.9	9.1	68.9	0.9	0.4	-1.5	2.1
Total		660.0	999.9	672.8		10.8	10.5	10.3
Mean 1981-2010		726.4				10.2		

During the 2014-2015 (October-June) growing season, precipitation was 605.5, which was fairly regular. In the spring months (March, April, and May), total rainfall was 201.6 mm, which was very important for the growth, flowering, and pollination of plants. Total precipitation in 2015 was 66.4 mm less compared with the historical mean. Temperature in this growing season was not a limiting factor. The mean annual temperature was 10.8 °C, slightly higher than the historical mean.

During the 2015-2016 (October-June) growing season, precipitation was 643.0 mm, which was 37.3 mm less than in the previous year. Rainfall was quite regular so that there was enough precipitation before and AS, which enabled timely tillage and good emergence. This season was characterized by a large amount of precipitation (999.9 mm), which was 273.5 mm higher than the historical mean. The large amount of rainfall and good rainfall schedule in this year had a positive influence on wheat yield, Temperature in this growing season was not a limiting factor. The mean annual temperature was 10.5°C, slightly lower than in the previous year and slightly higher than the annual mean.

During the 2016-2017 (October-June) growing season, total rainfall was 501.1 mm, which is 141.1 mm and 104.6 mm less than in the previous two seasons, respectively. The rainfall schedule was quite regular, so there was enough rainfall before and AS, which enabled timely tillage and sowing, as well as good sprouting. This season was characterized by 672.8 mm total rainfall, which was 327.1 mm less than in the previous year and at the level of total precipitation in 2015. Mean temperature in this year was 10.3°C, slightly lower than in previous years but within the range of the historical mean. This year was characterized by a colder winter compared with the previous 2 yr and the mean monthly temperature was -1.5°C in December and -6.6°C in January; this represented no risk of freezing for the crops.

In terms of total precipitation and its distribution during crop growth and temperature conditions, the 2015-2016 growing season can be distinguished as the most suitable for wheat.

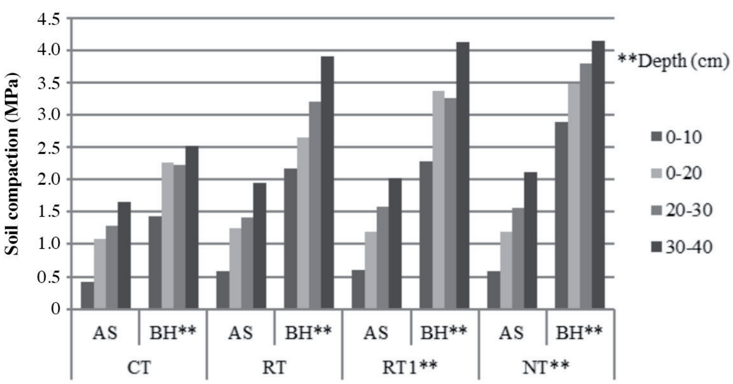
RESULTS AND DISCUSSION

Soil compaction

Soil compaction in all seasons was significantly influenced by the tillage system, measurement time, and depth. Figure 1 shows soil compaction for 2014-2015 as related to the tillage system, measurement time, and soil depth.

Mean soil compaction in 2014-2015 was 2.13 MPa. The highest mean soil compaction (2.47 MPa) was measured in NT and was significantly higher than in RT and CT. Nonsignificant differences were found between the RT and RT1 systems and the RT1 and CT systems for mean soil compaction. Mean soil compaction values BH were significantly higher than those AS. Mean soil compaction increased with increasing measurement depth from 1.37 MPa (0-10 cm) to 2.80 MPa (30-40 cm) and these differences were significant. The tillage system (A) × Measurement time (B) interaction showed very significant differences in all soil tillage systems. The A × Soil depth (C) interaction was the most expressed in all tillage systems between the 0-10 and 10-20 cm depths and differences were significant, while differences between

Figure 1. Influence of tillage system, measurement time, and depth on soil compaction in 2014-2015.



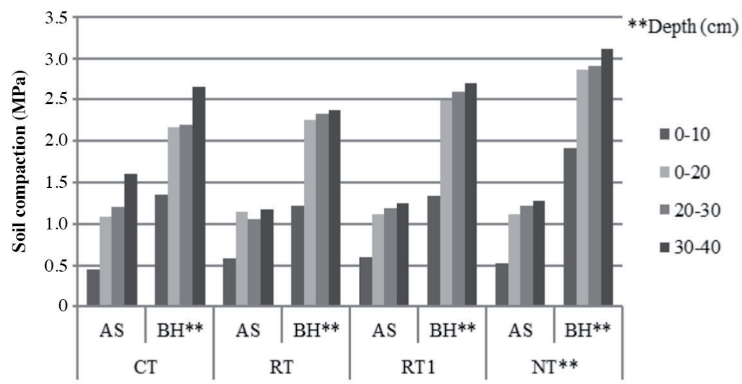
CT: Conventional tillage; R: reduced tillage; RT1: disc harrowing; NT: no-tillage; AS: after sowing; BH: before harvesting.
**Significant at $p \leq 0.01$.

the 10-20 and 20-30 cm depths were nonsignificant. The differences in soil compaction between 20-30 and 30-40 cm in RT and RT1 were very significant, while differences in CT and NT were significant. The B × C interaction showed very significant differences; therefore, the lowest mean compaction for all the processing systems (0.55 MPa) was measured at 0-10 cm after wheat sowing and the highest (3.67 MPa) at 30-40 cm before wheat harvest. The A × B × C interaction showed very significant differences. The lowest soil compaction (0.42 MPa) was measured in the CT system at 0-10 cm AS and the highest (4.14 MPa) was for the NT system at 30-40 cm BH.

Figure 2 shows soil compaction for 2015-2016 according to the tillage system, measurement time, and depth. Mean soil compaction in 2015-2016 was 1.66 MPa, which was 0.47 MPa lower than in the previous year. The highest mean soil compaction value (1.87 MPa) was measured in the NT system and was significantly higher than other tillage systems, which showed nonsignificant differences. Mean soil compaction values measured BH were significantly higher than those measured AS. Mean soil compaction increased as depth increased from 0.99 MPa (0-10 cm) to 2.02 MPa (30-40 cm); these differences were therefore significant. The A × B interaction showed very significant differences in all tillage systems, except RT. The A × C interaction in all tillage systems was expressed the most between 0-10 and 10-20 cm and these differences were significant, while the differences between 10-20, 20-30, and 30-40 cm in the RT system, RT1, and NT were nonsignificant. The B × C interaction showed very significant differences, so the lowest mean compaction for all tillage systems (0.54 MPa) was measured at 0-10 cm AS and the highest (3.67 MPa) at 30-40 cm BH. The A × B × C interaction showed very significant differences. The lowest soil compaction (0.45 MPa) was measured in the CT system at 0-10 cm AS, and the highest (3.11 MPa) was in the NT system at 30-40 cm BH. Lower mean compaction and smaller differences for the soil depth profile in this year compared with the previous year were caused by higher precipitation and its distribution.

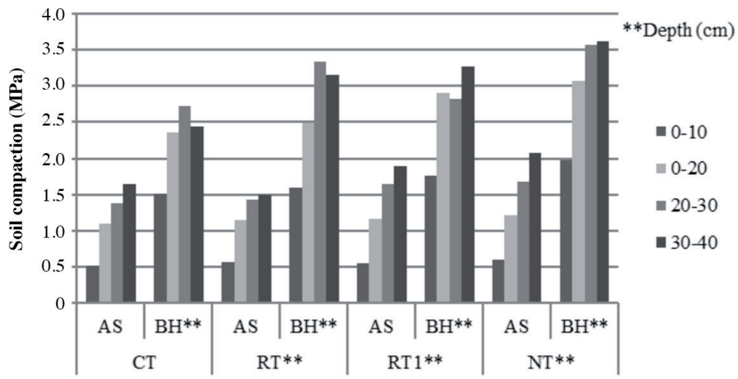
Figure 3 shows soil compaction in 2016-2017 according to the tillage system, measurement time, and depth. Mean soil compaction in 2016-2017 was 1.96 MPa, which was 0.17 MPa lower than in 2014-2015 and 0.30 MPa higher than in 2015-2016. The highest mean soil compaction (2.22 MPa) was measured in NT and was significantly higher than other tillage systems. The RT and RT1 systems, in which nonsignificant differences were found, had significantly higher compaction than CT. Mean soil compaction values measured BH were significantly higher than those measured AS. Mean soil compaction for all tillage systems significantly increased up to a depth of 20-30 cm, so that the differences in soil compaction between 20-30 and 30-40 cm were at the limit of statistical significance. The A × B interaction showed very significant differences in all tillage systems. The A × C interaction in all processing systems was the most expressed up to 30 cm and these differences were very significant. In the CT, RT, and NT treatments, differences in compaction between 20-30 and 30-40 cm were nonsignificant. The B × C interaction showed very significant differences, so that the lowest mean compaction for all tillage systems (0.56 MPa) was measured at 0-10 cm AS and the highest (3.12 MPa) at 30-40 cm BH. The A × B × C interaction showed very significant differences. The lowest soil compaction (0.52 MPa) was measured in the CT system at 0-10 cm AS, and the highest (3.61 MPa) in the NT system at 30-40 cm BH.

Figure 2. Influence of system tillage, measurement time, and depth on soil compaction in 2015-2016.



CT: Conventional tillage; R: reduced tillage; RT1: disc harrowing; NT: no-tillage; AS: after sowing; BH: before harvesting.
**Significant at $p \leq 0.01$.

Figure 3. Influence of system tillage, measurement time, and depth on soil compaction in 2016-2017.



CT: Conventional tillage; R: reduced tillage; RT1: disc harrowing; NT: no-tillage; AS: after sowing; BH: before harvesting.
**Significant at $p \leq 0.01$.

In every year of the 3-yr study, the highest values of soil compaction at 40 cm were determined for the NT system compared with other tillage systems. In every year, tillage systems, measuring time, and soil depth had a very significant impact on soil compaction. These results concur with the findings by Rusu et al. (2011), who highlight significantly higher values of soil compaction in wheat at depths of up to 45 cm in the NT system, and nonsignificant differences in other systems. Tolon-Becerra et al. (2011) measured soil compaction based on depth and number of tractor passages and pointed out a significant increase in soil compaction when depth increased to 60 cm. Similar results were obtained by Hernández et al. (2019). Our results concur with the findings by Bogunovic et al. (2014), who indicated that the tillage system has a significant influence on soil compaction in all profiles up to 60 cm, except in months with the highest precipitation. The same authors mention that the highest compaction was in the NT and minimal tillage systems, and the lowest was in the CT system. The specificity of our research is that it was carried out on soils of the Vertisol type, which is a type of heavy mechanical composition and very specific for cultivation. If this is compounded by the fact that the soil is not fertilized with organic fertilizers, but only with mineral fertilizers, and retains moisture in deeper layers, this creates conditions for this soil that is not cultivated or minimally cultivated, especially in the arable layer, to have higher compaction. Thus, Nawaz et al. (2013) point out that clay soils under lower moisture content are more susceptible to compaction than those with a sandy texture.

The highest soil compaction was recorded in the NT system because there was no tillage and some of the procedures of NT systems practiced in other countries were not used.

Soil moisture

Soil moisture is an important indicator of successful crop production; it was determined when measuring soil compaction and is expressed as mean values at a 0-40 cm depth. Table 3 gives an overview of soil moisture content according to tillage system, measurement time, and year of study.

Soil moisture content was significantly influenced by measurement time and years under study. However, nonsignificant differences were found between tillage systems for mean moisture content, which concurs with the results found by Blanco-Canqui et al. (2017). Mean moisture content for all tillage systems and years under study was 23.3% AS and 22.6% BH; these differences are very significant. The highest mean moisture content for all tillage systems and measurement times was in 2015-2016 (23.6%), and it was significantly higher than in the other 2 yr. It should be noted that the highest soil moisture content of all tillage systems was in 2015-2016 when the highest rainfall occurred during wheat growth and which had a positive effect on wheat yield. Our results are in line with the results reported by Pansak et al. (2008), who indicate that soil moisture is best stored in a CT system. However, our results do not concur with Martinez et al. (2011), who highlight the highest soil moisture values at depths of up to 50 cm in NT systems.

Table 3. Influence of tillage systems, measurement time, and year on soil moisture (%).

Tillage systems (A)		Moisture measurement time (B)	Years (C) 2014-2015	2015-2016	2016-2017	Mean AB
CT		AS	23.1	24.3	21.8	23.1
		BH	21.3	23.8	22.7	22.6
	Mean AC		22.2	24.1	22.3	22.8
RT		AS	23.9	25.0	21.4	23.4
		BH	20.8	21.7	21.5	21.3
	Mean AC		22.3	23.3	21.4	22.3
RT1		AS	24.7	25.5	20.7	23.6
		BH	21.1	23.6	20.6	21.7
	Mean AC		22.9	24.5	20.6	22.7
NT		AS	23.8	24.2	21.6	23.2
		BH	20.4	21.2	22.2	21.2
	Mean AC		22.1	22.7	21.9	22.2
Mean BC		AS	23.9	24.7	21.2	23.3
		BH	20.9	25.6	21.4	22.6
	Mean C		22.4	23.6	21.5	22.6

LSD	Level	A	B	C	A × B	A × C	B × C	A × B × C
	F test	923.84ns	217.27**	56.73**	217.27**	56.73**	65.98**	65.98**
	0.05	0.71	0.50	0.61	1.00	1.23	0.87	1.74
	0.01	0.95	0.67	0.82	1.34	1.64	1.16	2.32

CT: Conventional tillage; RT: reduced tillage; RT1: disc harrowing; NT: no-tillage; AS: after sowing; BH: before harvesting; ns: nonsignificant.
**Significant at $p \leq 0.01$.

Wheat yield

Wheat yield is conditioned by numerous factors, especially agrotechnical, agro-climatic, and genetic. Table 4 shows the yield of winter wheat according to the tillage system and year of study.

Wheat yield significantly depended on both the year and tillage system. The highest 3-yr wheat yield was achieved in the CT system (4033 kg ha^{-1}), and it was significantly higher than yield obtained in the NT system, and in RT and RT1 systems. There was nonsignificant difference in wheat yield between the RT and RT1 systems. The highest mean wheat yield for all tillage systems was in 2015-2016 (3744 kg ha^{-1}), and it was significantly higher than yield in 2014-2015. Nonsignificant differences were found between mean yields in 2014-2015 and 2016-2017. The lowest yield (2680 kg ha^{-1}) was in the NT system in 2014-2015, and the highest (4280 kg ha^{-1}) in the CT system in 2015-2016. Mean yield in the CT system was from 12.43% to 29.51% higher than yield in RT and NT systems.

The highest wheat yield was in the CT system in 2015-2016 when there was also the highest rainfall, the highest soil moisture, and the lowest compaction. Our results concur with the results reported by Shahzad et al. (2016), who obtained

Table 4. Influence of tillage system on winter wheat yield.

Tillage systems (factor A)	Years (factor B) 2014-2015	2015-2016	2016-2017	Mean of factor A	
	kg ha^{-1}			kg ha^{-1}	%
CT	3890	4280	3930	4033	100.00
RT	3410	3790	3410	3536	87.67
RT1	3370	3768	3460	3532	87.57
NT	2680	3140	2710	2843	70.49
Mean of factor B	3337	3744	3377	3486	
		A	B	A×B	
LSD	F test	24.929**	12.950*	12.950**	
	0.05	451.33	390.86	701.73	
	0.01	613.45	531.26	1062.53	

CT: Conventional tillage; RT: reduced tillage; RT1: disc harrowing; NT: no-tillage.
**Significant at $p \leq 0.01$.

higher wheat grain yields of 9.8% to 19.2% in the CT system compared with RT and NT. Dai et al. (2013) mention lower wheat yields in the NT system by 6% compared with CT systems; our results are consistent with these authors. Wozniak (2013) also indicated significantly higher wheat grain yields in the CT system compared with the RT and NT systems. A decrease in grain yield after direct sowing between 8% and 33% can be caused by higher soil compaction in the 15-25 cm depth layer (Rátonyi et al., 2005). Martinez et al. (2011) emphasize that in the favorable productive years, wheat yield was the highest in the CT compared with conservation tillage and NT systems.

Our results do not concur with the results found by Moraru and Rusu (2012), who point out that there are nonsignificant differences in wheat yields among soil treatment systems. Huang et al. (2012) mentioned significantly higher wheat yields in the NT than CT system.

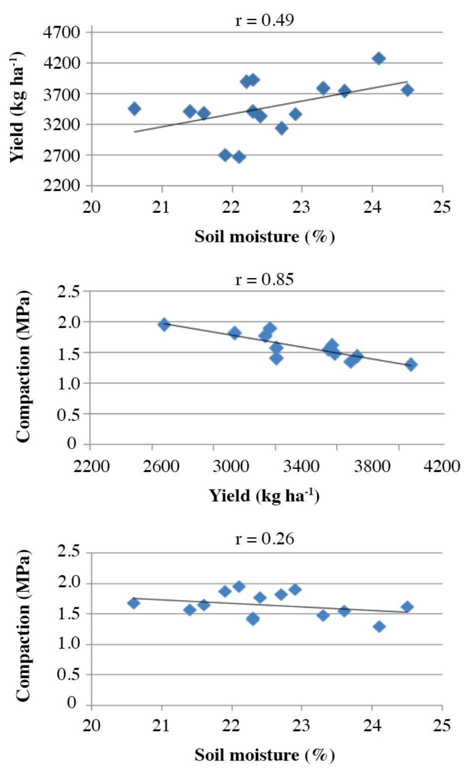
Plant yield strongly depends on the soil conditions in which the root system develops. The quality of soil conditions is defined by the favorable water-air regime, mechanical composition, and supply of soil nutrients. These conditions, especially in soils with heavy mechanical composition as in our case, can be achieved by quality and timely treatment and use of organic fertilizers. Only under such conditions is it possible to expect high yields of cultivated plants on these soil types. If this soil is not being tilled or is being minimally tilled, conditions for higher compaction and poor soil conditions are being created; this is reflected in lower yields of cultivated plants, which is evident in our research.

Correlation

Figure 4 shows the correlation between yield, soil moisture, and soil compaction. Water content in the soil is an indicator of water availability in the plant and an indicator of lower soil compaction; crop yield depends on these factors. In our 3-yr study, a mean positive correlation was found between soil yield and water content, as shown by Pearson's coefficient, r = 0.49. Vrindts et al. (2005) state that in areas with higher soil moisture variability, grain yields decrease.

Mean wheat yield had a strong negative correlation with soil compaction in which the coefficient of correlation was r = -0.85. Ramazan et al. (2012) point out that wheat yield decreases when soil compaction increases, which is consistent with our results.

Figure 4. Correlation between yield, soil moisture, and soil compaction.



The higher the soil moisture content, the lower the solid phase content, and thus less soil compaction. For higher wheat yields, lower compaction and higher water content are desirable. A weak negative correlation was found between these two properties, as shown by Pearson's coefficient, r = -0.26. The study by Nyéki et al. (2017) showed that changes in soil moisture content had the opposite effect on the natural compaction of clay, which is reflected in the wheat yield.

CONCLUSIONS

Tillage systems, measurement time, and soil depth had a significant impact on soil compaction. The highest soil compaction was recorded in the no-tillage (NT) system because there was no tillage and some of the procedures of NT systems practiced in other countries were not used. Soil compaction in all tillage systems measured after sowing the wheat was significantly lower than when measured before harvesting. Soil compaction increased as depth increased, reaching the highest value at 30-40 cm. Soil moisture content was significantly influenced by measurement time and year of study. However, nonsignificant differences were found between the tillage systems and mean moisture content.

Wheat yield significantly depended on year and tillage system. The highest 3-yr wheat yield occurred in the conventional tillage (CT) system, and it was significantly higher than yields achieved in other tillage systems. The highest wheat yield was in 2015-2016 in the CT system when there was also the highest rainfall, the highest soil moisture content, and the lowest compaction. A mean positive correlation was found between yield and soil moisture, a strong negative correlation between yield and soil compaction, and a weak negative correlation between soil moisture and soil compaction. If this soil is not being tilled or is being minimally tilled, conditions for higher compaction and poor soil conditions are being created; this is reflected in lower yields of cultivated plants, which is evident in our study.

Full tillage, including plowing and adequate pre-sowing soil preparation, is necessary to achieve satisfactory yields of wheat grown on a Vertisol.

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