EFFECT OF COVER CROPS AND SOIL TILLAGE METHODS FOR SOWING SPRING WHEAT (*TRITICUM AESTIVUM* L.) ON SELECTED SOIL PHYSICAL PROPERTIES

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Abstract. The aim of this study was to evaluate the variability of soil physical properties (available water, soil moisture, bulk density and soil capillary water capacity) at three depths (0–10, 10–20 and 20–30 cm) at the beginning of vegetation season and at harvest of spring wheat after different cover crops (white mustard, Nakielska cultivar) and soil tillage methods in a three–year study. The field experiment was conducted at the Brody Research and Education Station of the Poznań University of Life Sciences, Poland (52°26’ N; 16°17’ E). Multivariate statistical methods were used: canonical variable analysis and Mahalanobis distances. The most significant differences were observed between cover crop and spring wheat cultivated with direct sowing technology in 2012 and control without cover crop and spring wheat cultivation after ploughing technology in 2013 (soil depth at 0–10 cm); cover crop after skimming and simplified soil tillage for spring wheat in 2011 and no cover crop and direct–seeded spring wheat in 2012 (soil depth at 10–20 cm); and between cover crop after skimming and spring wheat cultivation in direct sowing technology in 2013 and cover crop in direct sowing technology and ploughing technology under spring wheat sowing in 2013 (soil depth at 20–30 cm). Canonical variables analysis provided a comprehensive assessment of the variation in the effect of cover crops and tillage method on many traits.
Keywords: *available water supply, bulk density, Mahalanobis distances, soil capillary water capacity, soil moisture*

Introduction

Soil type, cropping history, climatic conditions and previous tillage systems can significantly modify soil physical properties (Yuan et al., 2023; Kladivko, 2001). Soil tillage is one of the fundamental agrotechnical operations in agriculture, aiming to optimize and maintain the physical, chemical and biological properties of the soil. One of the purpose of tillage is to create the most favorable physical conditions for plant growth and seed germination (Jabro et al., 2011). It is very important for stimulating

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root growth, controlling soil moisture and soil temperature, alleviating soil compaction, and incorporating crop residues and manure. Soil physical properties can have a significant impact on physical, chemical and biological processes in the soil, so they should be maintained at optimal levels. Therefore, understanding of soil physical properties is essential throughout the growing season and after crop harvest. They can affect crop rotation, and the choice of soil tillage practices (Noor et al., 2020). The use of cover crops and various soil tillage methods is widely recognized as a key approach for improving soil fertility, reducing erosion, and increasing yield. Numerous studies, have been conducted in recent years to investigate the effect of cover crops and soil tillage methods on soil physical properties (Yuan et al., 2023; Kladivko, 2001). Cover crops are planted to protect and improve soil quality during periods when main crops are not growing (Jabro et al., 2011). They help reduce soil erosion, increase organic matter and improve soil structure. The effect of cover crop on soil water relationships is positive or neutral when rainfall infiltration is adequate and timely to replenish soil water reserves, so that the next crop is not stressed due to water. Soil water replenishment can occur before or after the cover crop is completed. The timing of termination becomes more critical when the probability of expected rainfall decreases (Garba et al., 2023). Intercropping reduces soil compaction at a depth of 0–10 cm and increases compaction at a depth of 10-20 cm (Acosta-Martinez et al., 1999). Live mulching of cover crops has various effects on the physical and chemical properties of the soil (Harasim et al., 2016), especially when it is introduced into the soil as mulch or cultivation, it affects all subsequent crops sown (Bocianowski and Majchrzak, 2019). Soil bulk density, available soil water, evaporation and aggregate stability are the most important parameters for assessing the impact of tillage systems on soil physical quality (Zarnoza et al., 2015). Reduced tillage maintains the ratio between soil porosity and bulk density (Josa et al., 2010) close to natural conditions. Reduced interference with the soil surface layer increases soil bulk density, improves water holding capacity and aggregate stability (McVay et al., 2006).

One of the many research problems is the analysis of quantitative traits of spring wheat plants with different genetic profiles depending on cultivation factors, i.e. cover crop, sowing, tillage. Analyzing the combinations of these treatments for all observed traits is an interesting aspect of the study. Therefore, in addition to the univariate statistical method that evaluates the results of the experiment, it is recommended to use multivariate methods that take into account the correlations of traits studied (Bocianowski and Liersch, 2021, 2022). The traits examined in this study (available water, soil moisture, bulk density and capillary capacity of soil) are very important from a practical point of view.

The research hypothesis assumed that the application of intercrop and the change of tillage for spring wheat sowing determined the increase in soil organic matter content, which improves the physical properties of the soil, such as water availability, soil moisture, bulk density, and capillary water capacity of the soil.

The purpose of this study was to conduct a multivariate characterization of phenotypic variation in 27 combinations of cover crops, tillage methods and years. Canonical variable analysis, based on a multivariate analysis of variance (MANOVA) model, was used for available water supply, soil moisture, bulk density, and soil capillary water capacity at two dates and three soil depths in a three–year experiment.

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Materials and methods

Experimental field

The field experiment was conducted at the Brody Research and Education Station of the Poznań University of Life Sciences, Poland (52°26’ N; 16°17’ E) during three growing seasons (2011, 2012 and 2013; the number “1” refers to the season 2011, “2” to 2012 and “3” to 2013) on Albic Luvisols soil (World reference base for soil resources, 2014) described as loamy sands overlying clayey material (12% clay, 19% silt and 69% sand). The research design was a split-plot with four replications (*Fig. 1*).

Figure 1. *The experimental design of spring wheat (Triticum aestivum L.) at the Brody Research and Education Station of the Poznań University of Life Sciences, Poland (52°26’ N; 16°17’ E)*

Treatments included a cover crop (white mustard, Nakielska cultivar) and a control (control without cover crop – Z, sowing a cover crop after skimming – S and direct sowing a cover crop – DSC). The cover crop was sown after spring wheat in the second decade of August at a rate of 20 kg ha^{-1} (for the first time in the summer of 2010) and left in the field until the spring of each year of the study. Spring wheat was evaluated with three tillage methods (direct sowing – DSW, simplified tillage (cultivation aggregate at a depth of 12–15 cm) – ST, spring plowing at a depth of 25 cm – PT) for four quantitative traits (available water reserve (mm), soil moisture (cm^3 100 cm^{-3}), bulk density (Mg m^{-3}) and soil capillary water capacity (%), at two terms (at the beginning of vegetation season and at harvest of spring wheat) and three soil layers of (0–10 cm, 10–20 cm and 20–30 cm).

The spring wheat cultivar Vinjett was sown at 400 seeds per 1 m^2 in all cropping systems. The size of each cultivation plot was 10 m long and 4.5 m wide, resulting in a total area of 45 m^2.

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Sowing dates for spring wheat depended on soil water conditions. Wheat was sown on March 25, 2011, March 23, 2012 and April 17, 2013 at a depth of 3–4 cm in all cropping systems.

Fertilization was uniform for all tillage systems and each experimental year (90 kg N ha^{-1}, 26 kg P_2O_5 ha^{-1}, 50 kg K_2O ha^{-1}). The herbicide program for the tillage systems consisted of pre–sowing and post–emergence applications. Before sowing, 1.5 L ha^{-1} of glyphosate herbicide + 1.5 L ha^{-1} of adjuvant As 500 SL was applied to all plots without tillage to control perennial and volunteer weeds. To control weeds during the growing season, a mixture of herbicides Lintur 70 WG (dicamba 65.9% + triasulfuron 4.1%) and Chwastox Extra 300 SL (MCPA 300 g L^{-1}) was applied at the BBCH 22 growth stage a rate of 150 g ha^{-1} and 1.0 L ha^{-1}, respectively. For disease control, the fungicide Falcon 460 EC (spiroxamine 250 g L^{-1} + tebuconazole 167 g L^{-1} + triadimenol 43 g L^{-1}) was applied to all plots at the BBCH 32 growth stage at a rate of 0.6 L ha^{-1}. For insecticide Fury 100 EW (zeta–cypermethrin 100 g L^{-1}) at a rate of 0.1 L ha^{-1} and Karate Zeon 050 CS (lambda – cyhalothrin) at a rate 0.1 L ha^{-1} were applied at the BBCH 61 growth stage. The spring wheat was harvested at full grain maturity in early August.

Sampling and measurements

Soil samples for physical property analyses were collected using Nitsch cylinders with a capacity 100 cm^3 and taken from each trench wall at the layers (0–10 cm, 10–20 cm and 20–30 cm) at two dates that corresponded to the tillering stage of spring wheat (BBCH 23), and at harvest (BBCH 89). Soil samples were taken randomly from four replicates and nine treatments. The soil samples were weighed and then dried in an over at 105°C. After drying the samples were reweighed to determined, soil bulk density (dry mass of soil divided by the volume of cylinder) and moisture content (difference in weight between moist and dry soil). To determine the water capacity the containers were set for capillary rise for a period of 24 h. After this time the simples were weighted again and based on the weight difference before and after drying, the capillary water capacity was determined (Mocek et al., 2000).

The properties of soil pores refer to the characteristics and features of the spaces between soil particles, which determine its ability to store, conduct and maintain water and air.

Weather condition

In order to compare the level and share of distribution, the dates of the year under study were compared with those of 1961–2010. In the 2010–2011 season, autumn vegetation took place under favorable thermal and moisture conditions conducive to the development of white mustard. From March to June, precipitation was below average, with deficits in April and May of 24.1 and 23.4 mm of precipitation, respectively, compared to multi–year averages. During the 2011–2012 growing season, autumn was warm and dry, with temperatures above the multi–year average for the period (September by 2°C and October by 0.9°C). In March, precipitation was 20 mm, half the multi–year average, and in April it was 22.9 mm (a difference of 1.5 mm). Precipitation in May and June exceeded the multi–year average, which compensated for their previous deficiencies. The last year of the study was characterized by favorable air temperature and natural precipitation in autumn, which favored the development of white mustard. The prevailing winter conditions in March delayed spring work and shortened the growing season of spring wheat. From May to August, air temperature was above the multi–year average, while precipitation from February to April was below the average for the period. Precipitation in May and June exceeded the multi–year average (by 12.4 and 63 mm, respectively), which partially compensated (especially in May) for moisture deficiencies in the earlier period. In July and August, the temperature was slightly higher than average, while the amount of precipitation was slightly lower than the average for this period. Assessing the course of weather conditions, it can be concluded that in terms of precipitation, 2011 was the least favorable year for wheat growth, while 2013 was the most favorable (*Fig. 2*).

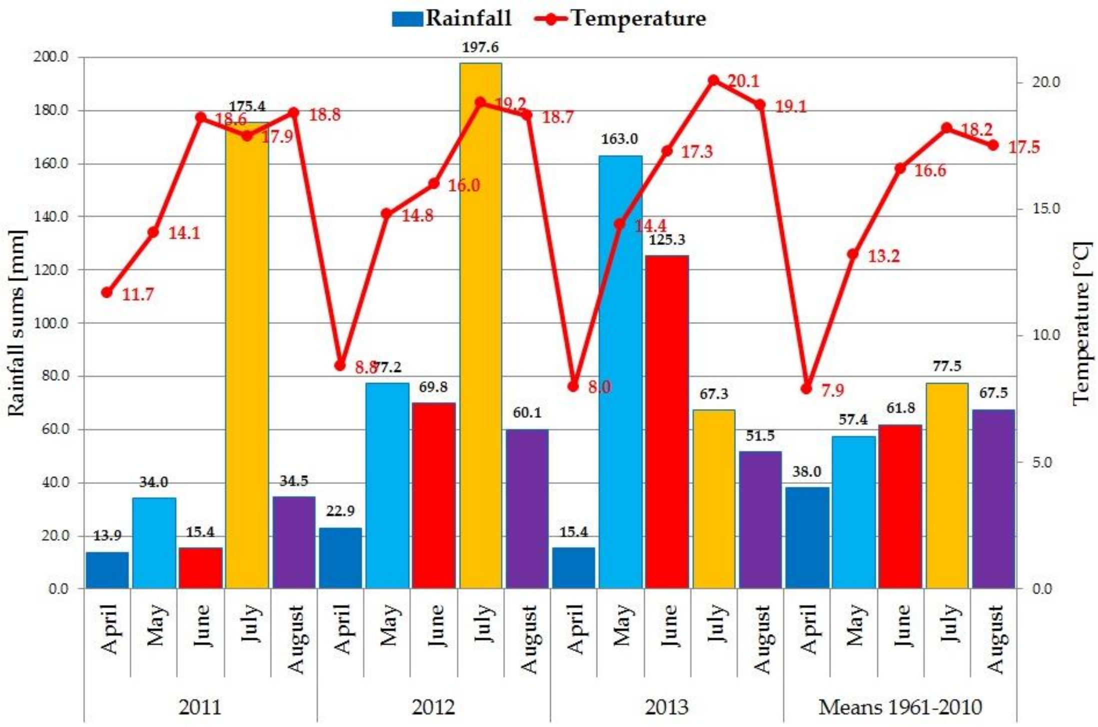

Figure 2. *Temperature and total precipitation in study years (2011–2013) at the Brody Meteorological Station*

Statistical analysis

The normality of the distributions of the studied traits was tested using the Shapiro-Wilk's normality test (Shapiro and Wilk, 1965). A three-way (year, cover crop and method of tillage) multivariate analysis of variance (MANOVA) was performed. Than the effects of the main factors studied (cover crop, method of tillage and years), as well as all interactions between them, were estimated using a linear model for three-way analysis of variance (ANOVA) for the traits. Relationships between observed traits were evaluated using Pearson correlation coefficients and tested using a *t*-test. Data were also analyzed using multivariate methods. Canonical variate analysis was used to provide a multivariate assessment of similarity for the treatments studied in a lower number of dimensions with the least possible loss of information (Rencher, 1992). The Mahalanobis distance has been proposed as a measure of the similarity of "polytrait" treatments (Seidler-Łożykowska and Bocianowski, 2012), the significance of which has been verified using the critical value Dα called "the least significant distance"

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(Mahalanobis, 1936). Mahalanobis' distances were calculated for the treatments studied. Pearson's simple correlation coefficients between the values of the first two canonical variables and the values of the individual original traits were estimated to determine the relative contribution of each original trait to the multivariate variability of the treatments analyzed. All analyses were performed using the GenStat v. 23 statistical package (VSN International Genstat, 2023).

Results

All quantitative traits studied have normal distributions, as well as multivariate normality. The results of MANOVA indicate that all factors (years: Wilk's $\lambda = 0.0088$, $F_{2;81} = 89.56$, $P < 0.0001$; cover crop: $\lambda = 0.2092$, $F_{2;81} = 10.98$, $P < 0.0001$; method of tillage for spring wheat: $\lambda = 0.1392$, $F_{2;81} = 15.5$, $P < 0.0001$) and their interactions (years × cover crop: $\lambda = 0.2791$, $F_{4;81} = 3.55$, $P < 0.0001$; year × method of tillage for spring wheat: $\lambda = 0.1665$, $F_{4;81} = 5.37$, $P < 0.0001$; cover crop × method of tillage for spring wheat: $\lambda = 0.1604$, $F_{4;81} = 5.51$, $P < 0.0001$; years × cover crop × method of tillage for spring wheat: $\lambda = 0.0820$, $F_{8;81} = 3.67$, $P < 0.0001$) were significantly different for all four traits in the two terms. ANOVA showed a statistically significant effect of years on all observed traits except soil capillary water capacity in May at two soil depths of 10–20 cm and 20–30 cm (*Table 1*). Cover crop was significant for available water supply and soil moisture at both terms at all soil depths, for soil capillary water capacity at 10–20 cm and 20–30 cm depths, and for bulk density in both months at 10–20 cm depth and in August at 20–30 cm depth. The tillage method was significantly different for available water supply, bulk density, soil capillary water capacity at both terms and soil moisture at the beginning of the vegetation season at a depth of 0–10 cm, for available water supply and soil moisture in May at a depth of 10–20 cm, available water supply and soil moisture in August at a depth of 20–30 cm. The year × cover crop × tillage method interaction for spring wheat was significant for all traits at both terms and at all three soil depths, except for bulk density in May at a depth of 20–30 cm (*Table 1*). It showed few statistically significant correlations between the observed traits. In general, no statistically significant correlations between the beginning of the vegetation season and the post–harvest period of spring wheat, except for available water supply at 0–10 cm and 20–30 cm depths and bulk density at 10–20 cm depth (*Table 2*). Available water supply was significantly positively correlated with soil moisture (by months) at all depths. On the other hand, bulk density was significantly negatively correlated with soil capillary water capacity (by terms) at all three soil depths (*Table 2*).

Table 1. *F-statistics from a three-way analysis of variance for observed traits*

Source of variation	d.f.	Available water supply		Soil moisture		Bulk density		Soil capillary water capacity	
		V[#]	VIII	V	VIII	V	VIII	V	VIII
The soil depth of 0–10 cm									
Year (Y)	2	1175***	68.5***	885.1***	31.2***	39.5***	37.8***	17.5***	38.3***
Cover crop (Cc)	2	16.11***	64.9***	17.78***	49.6***	0.86	1.09	1.12	2.72
Method of tillage (Mt)	2	43.96***	23.7***	27.71***	2.49	14.2***	19.6***	7.67***	17.3***
Y×Cc	4	6.15***	3.83**	6.78***	1.77	3.02*	5.53***	2.23	0.96
Y×Mt	4	9.94***	0.25	5.67***	1.6	16.8***	2.85*	8.72***	9.99***
Cc×Mt	4	3.97**	2.46	3.91**	8.05***	1.19	13.8***	5.65***	10.88***
Y×Cc×Mt	8	8.86***	2.91**	5.27***	2.59*	4.25***	4.55***	4.9***	5.41***

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The soil depth of 10–20 cm									
Year (Y)	2	913.0***	41.6***	595.4***	29.6***	62.8***	21.0***	2.81	89.6***
Cover crop (Cc)	2	52.93***	32.3***	73.83***	49.5***	10.8***	7.02**	3.42*	3.93*
Method of tillage (Mt)	2	25.88***	0.42	31.49***	0.37	4.2*	0.07	2.31	0.24
Y×Cc	4	17.69***	2	14.55***	0.91	0.66	1.32	2.01	7.97***
Y×Mt	4	16.95***	11.6***	14.59***	6.79***	2.49*	2.35	1.94	4.18**
Cc×Mt	4	30.48***	7.72***	29.73***	10.3***	1.47	1.23	2.03	3.22*
Y×Cc×Mt	8	6.73***	3.92***	8.96***	4.15***	5.89***	3.56**	2.76**	5.24***
The soil depth of 20–30 cm									
Year (Y)	2	30.01***	52.8***	17.25***	32.5***	14.7***	6.77**	2	57.4***
Cover crop (Cc)	2	5.36**	98.1***	4.17*	63.0***	0.05	6.89**	12.3***	6.83**
Method of tillage (Mt)	2	1.11	24.6***	1.43	27.8***	2.51	3.79*	2.17	3.14*
Y×Cc	4	3.03*	9.43***	3.73**	7.24***	9.18***	0.34	5.25***	2.1
Y×Mt	4	5.98***	8.1***	5.48***	8.02***	4.29**	2.03	2.24	3.76**
Cc×Mt	4	7.36***	14.3***	6.3***	7.78***	4.31**	3.6**	5.3***	10.3***
Y×Cc×Mt	8	2.64*	18.0***	2.12*	11.4***	0.52	7.01***	5.21***	7.68***

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; d.f. – the number of degrees of freedom; # V – beginning of vegetation season; VIII – harvest of spring wheat

Table 2. *Correlation coefficients between observed quantitative traits of soil under spring wheat cultivation in two terms and three depths of soil*

Trait	Term	The soil layer [cm]	Available water supply		Soil moisture		Bulk density		Soil capillary water capacity
			V#	VIII	V	VIII	V	VIII	V
Available water supply	VIII	0-10	0.59**						
		10-20	0.17						
		20-30	0.46*						
Soil moisture	V	0-10	0.99***	0.61***					
		10-20	0.99***	0.23					
		20-30	0.98***	0.41*					
	VIII	0-10	0.24	0.75***	0.26				
		10-20	0.01	0.93***	0.08				
		20-30	0.42*	0.98***	0.38				
Bulk density	V	0-10	0.69***	0.38*	0.62***	0.1			
		10-20	0.58**	-0.19	0.44*	-0.34			
		20-30	0.04	0.11	-0.13	0.11			
	VIII	0-10	0.52**	0.47*	0.53**	-0.18	0.33		
		10-20	0.42*	0.12	0.38	-0.24	0.44*		
		20-30	0.07	-0.01	0.08	-0.16	-0.04		
Soil capillary water capacity	V	0-10	-0.47*	-0.29	-0.43*	-0.07	-0.71***	-0.24	
		10-20	-0.13	-0.05	-0.05	0.011	-0.51**	-0.16	
		20-30	-0.16	-0.18	-0.09	-0.16	-0.54**	-0.13	
	VIII	0-10	-0.45*	-0.54**	-0.46*	-0.10	-0.17	-0.63***	0.03
		10-20	-0.30	-0.45*	-0.27	-0.17	-0.35	-0.72***	0.15
		20-30	-0.20	-0.37	-0.20	-0.23	-0.01	-0.74***	0.12

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; #V – beginning of vegetation season; VIII – harvest of spring wheat

Individual traits contributed differently to the joint multivariate variability. The CVA results for treatments studied are shown in *Table 3*. The first two canonical variables together explained 86.73%, 88.96% and 68.66% of the total inter–treatments variability at the first, second and third soil depths, respectively (*Table 3; Figs. 3, 4* and *5*).

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Table 3. *Correlation coefficients between the first two canonical variables and original traits in two terms and three depths of soil*

Trait	Month	0-10 cm soil depth		10-20 cm soil depth		20-30 cm soil depth	
		V_1	V_2	V_1	V_2	V_1	V_2
Available water supply	V#	-0.98***	-0.11	-0.99***	0.13	-0.64***	0.38
	VIII	-0.71***	0.51**	-0.29	-0.87***	-0.95***	-0.20
Soil moisture	V	-0.98***	-0.10	-0.98***	0.07	-0.57**	0.35
	VIII	-0.33	0.89***	-0.12	-0.81***	-0.92***	-0.33
Bulk density	V	-0.72***	-0.06	-0.55**	0.31	-0.28	0.20
	VIII	-0.56**	-0.47*	-0.44*	-0.11	0.01	0.76***
Soil capillary water capacity	V	0.51**	0.13	0.19	-0.11	0.25	-0.16
	VIII	0.53**	0.02	0.38	0.62***	0.38	-0.64***
Percent variation		80.7	5.67	77.49	11.47	51.31	17.35

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; V_1 - first canonical variable; V_2 - second canonical variable; #V – beginning of vegetation season; VIII – harvest of spring wheat

The soil layer 0–10 cm

Figure 3 shows the variation of the traits of the studied treatments in the system of the first two canonical variables at the first soil depth (0–10 cm). In the graph, the coordinates of the point of a given treatment are the values of the first and second canonical variables, respectively. The largest significant linear relationship with the first canonical variable was found for the soil capillary water capacity in both months (positive relationships), as well as available water supply and bulk density in both months, and soil moisture in May (negative) (*Table 3*). The second canonical variable was significantly positively correlated with available water supply, soil moisture, and negatively with bulk density (only during wheat harvest) (*Table 3*). The greatest variation in term of the four traits at the two combined dates (measured Mahalanobis distances) was found for the DSC–DSW–2 and Z–PT–3 (the Mahalanobis distance between them was 22.23). The highest similarity was found for treatments Z–ST–1 and DSC–DSW–1 (0.87).

The soil layer 10–20 cm

Figure 4 shows the variation in the traits of treatments studied in the pattern of the first two canonical variables in the second soil layer (10–20 cm). A significant linear negative relationship with the first canonical variable was found for available water supply and soil moisture (in May) and bulk density (in both months) (*Table 3*). The second canonical variable was significantly negatively correlated with available water supply and soil moisture (in August), and positively correlated with soil capillary water capacity VIII (*Table 3*). The greatest diversity in terms of the four traits at the two combined dates was found for treatments S–ST–1 and Z–DSW–2 (19.12). The greatest similarity was found for the Z–PT–1 and S–DSW–1 (1.36).

The soil layer 20–30 cm

Figure 5 shows the variation of traits for the treatments studied in the pattern of the first two canonical variables in the third soil depth (20–30 cm). The largest negative correlations with the first canonical variable was found for available water supply and soil moisture in both months (*Table 3*). The second canonical variable was negatively

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correlated with soil capillary water capacity, and positively correlated with bulk density during wheat harvest (*Table 3*). The greatest variation was found for the S–DSW–3 and DSC–PT–3 (11.11), while the greatest similarity was found for the Z–DSW–2 and DSC–ST–2 (1.44).

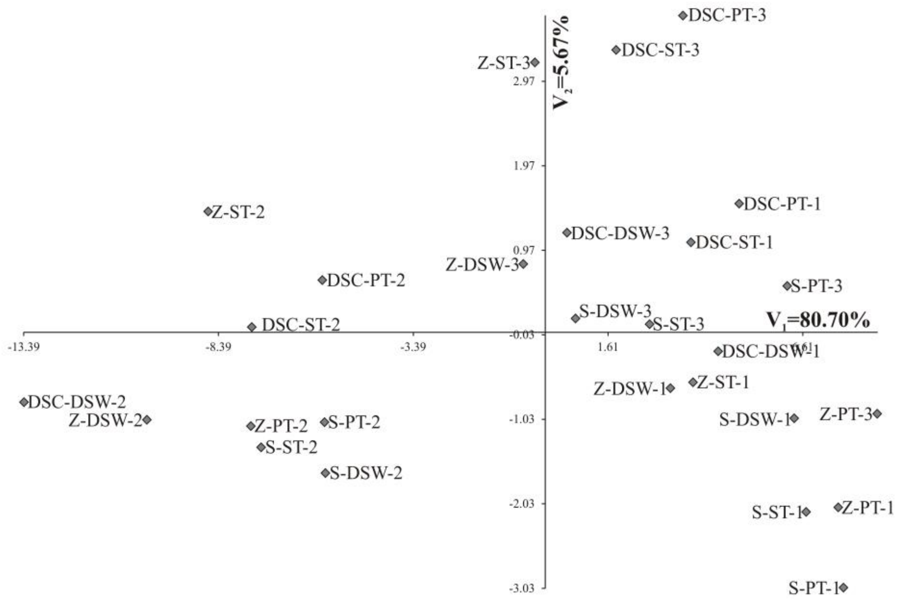

Figure 3. *Distribution of spring wheat treatments in the two first canonical variables in the 0-10 cm soil layer (cover crop: Z – zero (without cover crop), S – skimming, DSC – direct sowing; method of tillage for spring wheat: DSW – direct sowing, ST – simplified tillage, PT – spring ploughing; years: 1 – 2011, 2 – 2012, 3 – 2013)*

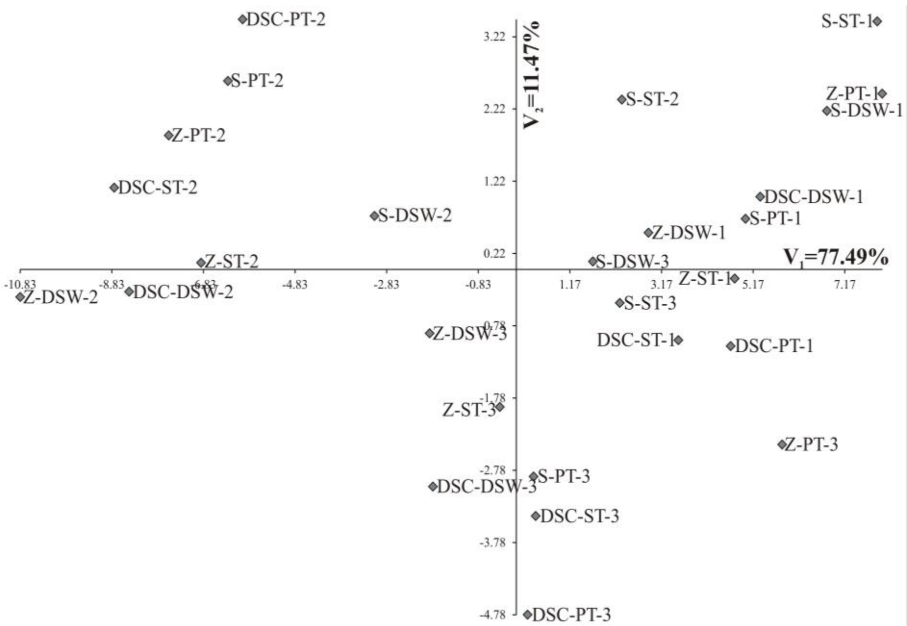

Figure 4. *Distribution of spring wheat treatments in the two first canonical variables in the 10-20 cm soil layer (cover crop: Z – zero (without cover crop), S – skimming, DSC – no tillage; method of tillage for spring wheat: DSW – direct sowing, ST – simplified tillage, PT – spring ploughing; years: 1 – 2011, 2 – 2012, 3 – 2013)*

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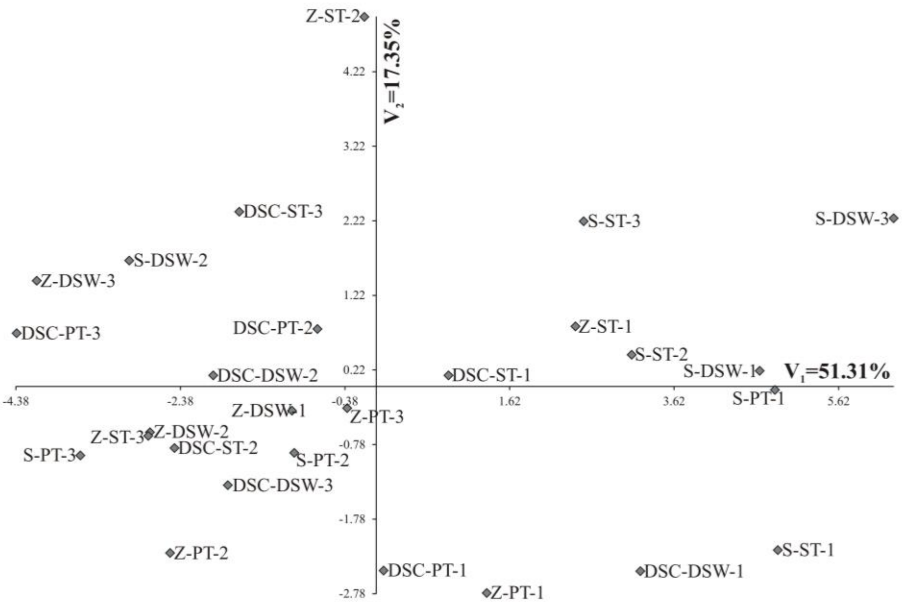

Figure 5. *Distribution of spring wheat treatments in the two first canonical variables in the 20-30 cm soil layer (cover crop: Z – zero, S – skimming, DSC – no tillage; method of tillage for spring wheat: DSW – direct sowing, ST – simplified tillage, PT – spring ploughing; years: 1 – 2011, 2 – 2012, 3 – 2013)*

Discussion

In the present study, a statistically significant effect of tillage on soil capillary water capacity, available water reserve, and bulk density was observed during the growing season of spring wheat. A similar relationship was previously obtained by Majchrzak and Skrzypczak (2010). Analysis of soil physical properties indicates that capillary water holding capacity is higher in no–tillage than with cultivated plow. However, this has not been statistically confirmed. Analysis of soil bulk density after wheat harvest showed an upward trend of the observed trait in the no–till technology. The effect of different tillage systems on water dynamics at three depths was analyzed (Sławiński et al., 2012). At a depth of 5 cm, a significant difference was found between water content in conventional and reduced tillage. Higher water content was observed in reduced tillage for almost the entire measuring period, with differences of 10%.

In a study by Fabrizzi et al. (2005), it was that over-cultivation increase soil bulk density and reduces soil moisture. Wang et al. (2015a) proved that soil bulk density is modified by tillage. It was lower in reduced tillage (0.07 g cm^{-3}) compared to no–tillage at a depth of 0–20 cm.

The results indicate that the use of cover crops has a significant effect on the soil's capillary water capacity and bulk density at different depths. Singh et al. (2018) came similar conclusions, indicating the importance of the effect of soil cultivation and post-harvest residue management on capillary water capacity and soil bulk density. In contrast, Sindelar et al. (2019) showed that the removal of cover crops and crop residues had no effect on soil bulk density at any of the depths considered.

According to Klopp et al. (2022), the effect of catch crops on soil physical properties depends on a number of factors, such as climate, soil type, tillage system, and the way crop residues are managed. The authors state that the removal of post–harvest residues

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from the field can lead to an increase in the soil bulk density and a decrease in porosity and water capacity. Removal of crop residues can lead to a deterioration of soil structure and a decrease in the stability of soil aggregates, which in turn increases soil erosion. Soil porosity also increased as the amount of crop residue increased. Mulched soils often contain more microspores, resulting in faster drainage than unmulched soils. On the other hand, addicting crop residues to the soil surface reduces the bulk density of the soil due to the accumulation of residues in the surface soil. Few conventional agricultural practices that compact the soil lead to increased soil strength and reduced root penetration. Residue management on these soils typically reduces soil compaction and strength and makes the soil more permeable. High root density in surface soil can also contribute to reduced soil density (Nascente et al., 2015). Biopores formed from dead roots reduce soil density and improve oxygen diffusion, water infiltration and gas exchange (Calonego and Rosolem, 2008; Irmak et al., 2018). These results suggest that increasing the amount of crop residues can lead to improved soil physical properties.

The results showed that cover crop significantly affected the available soil capillary water capacity in the 10–20 cm and 20–30 cm water supply ranges at both terms at all soil depths. Removal of the residue significantly reduced the amount of water available to plants at 0–5 cm and 5–10 cm depths. Plant–available water decreased by 32% at a depth of 0–5 cm and by 21% at a depth of 5–10, but crop residue removal had no plant–available water below a depth of 10 cm. This significant difference suggests that cover cropping was unable to offset the negative effects of residue removal on water retention, pore size distribution and available water, which was also strongly correlated with volumetric water content at 0.033 MPa at all depths (Sindelar et al., 2019). The authors suggest that cover cropping would mitigate the effects of residue removal on water retention, pore size distribution and plant–available water. They are very few studies on the potential of cover crops to offset crop residue removal. A study by Wegner et al. (2015) found that cover crops did not offset the negative effects of high rates of corn residue removal on water retention. Majchrzak et al. (2021) suggested that cover crops lowered soil moisture and reduced crop yields. In contrast, Wang et al. (2015b) claim that deep–rooted cover crops are particularly effective in increasing soil water storage capacity.

In the current research, cover crop and tillage method interaction was significant for all traits at both terms and at all three soil depths, except for bulk density in May at a depth of 20-30 cm. Brant et al. (2009) indicate changes in physical properties after the introduction of intercrops into the soil. In a study by Haruna and Nkongolo (2015), intercrops stimulated an increase in soil moisture only in the top (0–10) cm of the soil, while their effect in deeper layers was found to be insignificant (Irmak et al., 2018). At the soil depths analyzed, cover crops reduced soil density, with white mustard having the strongest effect on reducing this density. The biomass of cover crops increased capillary porosity and soil water reserve, which was also confirmed by Tomaszewska (2002) and Korsak-Adamowicz (2004). Differences in the physical properties of soil at different depths are common and result from various factors. Soil is a dynamic system that undergoes changes as you go deeper into the soil profile. The top layer of the soil are more exposed to the influence of rainfall and evaporation, which is why they are often more moist. However, deeper in the soil profile, the moisture may be less variable and more stable (Malecka et al., 2012). Soil water capacity depends on the pore structure and the presence of organic materials (Salem et al., 2015; Chen et al., 2017; Are et al., 2021). The top layers of the soil often have better conductivity for both water

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and air compared to deeper soil layers. Bulk density varies with different layers of soil due to variations in soil properties, composition, and method of tillage (Lawal, 2017; Xue et al., 2018). Generally, soil bulk density tends to change as you move deeper into the soil profile.

Conclusion

The results of multivariate analyses presented here are a convincing illustration of the response of the applied factors to the variability of the observed traits. The canonical variable analysis was shown to be effective. This is due to the fact that the variables explained a significant part of the total variability (86.73%, 88.96% and 68.66% in the first, second and third soil depths, respectively). In addition, three groups of treatments were obtained, classified according to the years of study. This indicates the reliability of the method, which confirms its widespread use by breeders and geneticists (Seidler-Łożykowska et al., 2013; Nowosad et al., 2016; Bocianowski et al., 2018, 2019; Wrońska-Pilarek et al., 2018, 2019, 2022). In the research presents here, the greatest diverse in terms of all the four traits at two combined dates (measured Mahalanobis distances) was found for: cover crops and spring wheat grown with direct sowing technology (2012) and without cover crops and spring wheat grown after ploughing cultivation technology (2013) (soil depth at 0–10 cm), cover crops after skimming and simplified soil tillage for spring wheat (2011) and without cover crops sowing and spring wheat in direct sowing technology (2012) (soil depth at 10–20 cm), as well as sowing of cover crop after skimming and spring wheat cultivation in direct sowing technology (2013) and cover crop in direct sowing technology and ploughing technology under spring wheat sowing (2013) (soil depth at 20–30 cm). The soil layer of 0–30 cm is an essential zone were crucial changes in the physical properties of the soil occur. Understanding this changes is vital for sustainable soil management and preserving its quality to support healthy plant growth and environmental conservation.

Summary

In conclusion, the presented results provide valuable knowledge for farmers and agricultural scientists. Based on the research performed, it can be concluded that a properly selected tillage method can help improve the physical properties of the soil. However, it should be remembered that each method has its own advantages and disadvantages, so it is important to choose the one that best suits the soil and climatic conditions.

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