INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2025, 39, 73-86
doi: 10.31545/intagr/195906

Effects of cover crops and tillage methods on selected physical and water retention properties of Luvisol

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Received June 17, 2024; accepted November 13, 2024

Abstract. The study aimed to assess the impact of spreading cover crops and different tillage methods on specific physical and water retention properties of Luvisol. The experiment analysed the influence of two factors on the tested properties. The first-order factor was the sowing of cover crops; three levels were analysed in the experiment: without cover crop, field pea sown after the wheat harvest, and white mustard sown after the wheat harvest. The second-order factor was the tillage method for intercrop seeding and spring wheat; four levels were analysed: conventional tillage, strip-till, reduced tillage, and no-till. After three years of the field experiment, four composite bulk samples with disturbed structure and eight core samples (100 cm^3) with undisturbed structure were taken from the humus horizon (15 cm) of each treatment. The collected soil samples were used to analyse the total carbon content, basic physical properties, and water retention properties. The use of the cover crops positively influenced the soil properties, whereas the simplified cultivation had a negative effect. The impact of sowing the cover crops was greater than that of the tillage method. Despite the statistical significance of the impact of the tested factors, their practical impact seems to be negligible.

Keywords: cover crops, tillage method, Luvisols, water retention properties

1. INTRODUCTION

Luvisols are the most important group of soils in Poland, covering ~45% of its area. They are mostly used for agricultural purposes, as they are characterised by average to good agricultural value and are suitable for growing wheat, maize, and rapeseed (Kabała, 2023). Technological progress and the need to optimise costs are forcing conventional cultivation methods to be modified. Various simplified types of cultivation are increasingly being used, such as reduced tillage, strip-till, and no-till. The use of simplified cultivation is controversial for reasons that include ambiguous research assessments of their impact on yields and soil properties. Such ambiguities are reported by Kaczmarek *et al.* (2013) and Tamm *et al.* (2016). The key soil properties that change ambiguously in response to changes in cultivation methods include, among others, soil bulk density, porosity, and total carbon content. Some authors claim that reduced tillage and no-till increase density (Fabrizzi *et al.*, 2005; Taser and Metinoglu, 2005, Rasouli *et al.*, 2012). Rasouli *et al.* (2012) conclude that this impact is statistically insignificant. A separate issue is the negative impact that monocultures have on soil properties. The negative effects of monocultures include reduced macro- and micronutrient contents in the soil, deterioration in soil's physical and biological properties, increased shares of weeds, and compensatory adaptations by pest species (Głąb and Kulig, 2008; Gou *et al.*, 2020; Weisberger *et al.*, 2019). Other authors also report negative effects of monocultures on the productivity of the agrosystem (Kwiatkowski *et al.*, 2020). These effects can be counteracted by the use of cover crops (Chalise *et al.*, 2019; Griffin *et al.*, 2000; Heyman *et al.*,

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2019; Weisberger *et al*., 2019). Their use can also prevent the leaching of nutrients (Thorup-Kristensen, 1994). Moreover, some authors claim that cover crops contribute to improving soil structure and physical properties – especially moisture, total porosity, and density (Sharratt, 2002). Various authors also report that cover crops play a considerable role in reducing the erosion often associated with monoculture crops (Espejo-Pérez *et al*., 2013; Gómez *et al*., 2011). Other reports show that plant matter has a multifaceted effect on soil properties that depends on, among other things, its amount, type, and chemical composition as well as when and by what method it is incorporated into the soil (Jian *et al*., 2020). The widespread occurrence and high fertility of Luvisols make them important to the national food production so they also hold great possibilities in the context of the potential sequestration of organic carbon in Poland (Świtoniak, 2023). Soil retention capacity and thus bulk density and porosity are one of the most important soil properties influencing resource use efficiency, nutrient cycling, crop productivity, yield stability, and environmental quality (Minasny and McBratney, 2018; Ogle *et al*., 2019). There are papers in the literature dealing with the impacts that sowing cover crops and tillage methods have on the physical and retention properties of soils. Among these articles, there are few that deal with Luvisols in central Europe. Since these soils are widely represented on its territory and given the huge diversity of this type of soil (Kabała, 2023), there is a need to fill this gap. Furthermore, available articles often provide contradictory results (Bielińska and Mocek-Płóciniak, 2012; Włodek *et al.,* 2012); hence, exploration of this issue is still necessary.

The study aimed to assess the impact of sowing cover crops and various tillage methods on selected physical and water retention properties of Luvisol. The research hypotheses assumed that the use of cover crops would have a positive effect, whereas simplified tillage cultivation would negatively affect soil properties, and the impact of sowing cover crops would be greater than that of the tillage method.

2. MATERIALS AND METHODS

2.1. Experimental scheme

The study was based on an experiment conducted in 2017-2019 at Zakład Doświadczalno-Dydaktyczny Brody (52°26’N; 16°17’E) in central Poland. The experiment was carried out in a split-plot design in four replicates totalling 48 plots, each of 45 m^2. The first-order factor was intercrop seeding (3 factor levels). The second-order factor was the tillage method for intercrop seeding and spring wheat (4 factor levels, Table 1). Three levels of the first-order factor were investigated in the experiment: WCC – without cover crop, FP – field pea sown after the wheat harvest, and WM – white mustard sown after the wheat harvest (Table 1). Spring wheat was grown on all plots, regardless of the experimental factors. Wheat at this site has been sown since 2006. Spring wheat was usually sown at the beginning of April and harvested at the beginning of August. The tillage factor was examined in four variants: CT – conventional plough tillage, ST – strip-till, RT – reduced tillage, NT –

Table 1. Scheme of the experiment

Cover crop variant	Tillage method	Cultivation system
WCC	CT	Plowing for drilling spring wheat, primary tillage after wheat harvest
	RT	Direct drilling of spring wheat, primary tillage after wheat harvest
	ST	Strip-till for drilling spring wheat, without primary tillage after wheat harvest
	NT	Direct drilling of spring wheat, without primary tillage after wheat harvest
FP	CT	Plowing for drilling spring wheat, primary tillage for drilling field pea
	RT	Direct drilling of spring wheat, primary tillage for drilling field pea
	ST	Strip-till for drilling spring wheat, strip-till for drilling field pea
	NT	Direct drilling of spring wheat, direct drilling of field pea
WM	CT	Plowing for drilling spring wheat, primary tillage for drilling white mustard
	RT	Direct drilling of spring wheat, primary tillage for drilling white mustard,
	ST	Strip-till for drilling spring wheat, strip-till for drilling white mustard
	NT	Direct drilling of spring wheat, direct drilling of white mustard

WCC – without cover crops, FP – field pea, WM – white mustard, CT – conventional tillage, RT – reduce tillage, ST – strip-till, NT – no tillage.

Table 2. Selected meteorological data for growing season 2017-2019

Meteorological parameter	Growing season 2017-2019						Total percipitation (mm)
	IV	V	VI	VII	VIII	IX	
Year	2017						
Average temperature (C°)	7.7	14	17.7	18.4	18.9	13.6	
Total precipitation (mm)	25.7	49.2	106	160.8	150.6	54.8	547.1
Average relative air humidity*	80.7	80.4	79.5	82.1	81.7	90	
Year	2018						-
Average temperature (C°)	12.9	17.1	19.1	20.7	21.4	15.9	
Total precipitation (mm)	65.3	19.2	31.5	134.9	20	60.7	331.6
Average relative air humidity	79.2	61.5	60.3	62.8	58.8	68.5	
Year	2019						-
Average temperature (C°)	10.4	12	22.3	19.3	20.7	14.5	
Total precipitation (mm)	11.9	77.8	8.4	63.3	28.2	63.8	253.4
Average relative air humidity 200 cm	56.5	72.8	59	62.2	65.4	74.8	
	Average for 2017-2019						
Temperature (C°)	10.3	14.4	19.7	19.5	20.3	14.7	-
Total precipitation (mm)	34.3	48.7	48.6	119.7	66.3	59.8	
Relative air humidity 200 cm	72.1	71.6	66.3	69	68.6	77.8	

*Measured at a height of 200 cm.

no-till. Except the strip-till variant, in all the soil tillage methods, spring wheat and cover crops were sown with a universal seed drill at a spacing of approximately 18 cm. In the CT factor, wheat was sown after spring ploughing to a depth of ~25 cm, and after harvest, regardless of the cover crop factor, primary tillage to a depth of ~10-12 cm was performed. In reduced tillage, primary tillage for cover crops was performed with a KOS cultivator consisting of a cultivator with rigid tines, surface levelling discs, and a string roller (working depth 10-12 cm), and wheat was directly drilled. Strip-till was performed by a machine built at the Department of Agronomy of the University of Life Sciences in Poznań. The tiller comprised a rigid tine, a pair of discs to catch the soil behind the tine, and a tire roller. The inter-tine spacing was 36 cm, of which the strip tilled and cleared of plant residue comprised ~15-16 cm, and the width of the strip covered with mulch comprised 20-21 cm. In strip-till, the spacing of plant rows was 10 cm between rows in the tilled strip and 26 cm between the strips. In this variant, the tillage depth was ~20 cm. In the no-till variant, the cover crop was direct drilled into the wheat residue, and wheat was directly drilled into the cover crop residue; in the factor with no cover crop, wheat was directly drilled into the soil. The cover residue remained on the field surface about 40% only on the objects with direct sowing of the cover crop and spring wheat and on the objects with strip tillage. On objects with conventional and reduced tillage, the residues of the intercrop were introduced into the soil. Albic Luvisol (Epiarenic, Cutanic, Ochric) soil, formed from sandy loams of Würm glaciation, was found to be present on all analysed plots (IUSS WRB, 2022).

Selected meteorological data from the weather station of Agricultural Experimental Station Brody are given in Table 2.

2.2. Soil sampling and measurements

After three years of the field experiment, one composite bulk sample (from each plot) with disturbed structure and two (from each plot) core samples (100 cm^3) with undisturbed structure were taken from the Ap horizon (15 cm). In total, 96 core samples and 48 samples with disturbed structure were collected. The soil samples were collected just before wheat harvest. The sampling date was chosen to eliminate the compacting effect of agricultural machinery. All methods used are given in Table 3.

2.3. Statistical analysis

Firstly, the normality of the distributions of the 11 studied properties was tested using the Shapiro-Wilk normality test (Shapiro and Wilk, 1965). A multivariate analysis of variance (MANOVA) was performed based on the following model using a MANOVA procedure in GenStat 23. Subsequently, two-way analyses of variance (ANOVA) were conducted to determine the main effects of tillage and cover crop as well as tillage-cover crop interaction in the values of observed properties, independently for each property Moreover, Fisher's least significant differences

Table 3. Methods and procedures used in the experiment

No.	Analysis	Method/Norm/References	Key parameters of the method Kind of samples Number of replicates
1.	Preparation of samples for analysis of particle density, maximum hygroscopic capacity, total carbon content	(PN-ISO 11464:1999).	Samples with a disturbed structure were dried at room temperature, than crushed by hand and sieved through a sieve with a diameter of 2 mm
2.	Texture analysis	Sand fractions by sieve method. Silt and clay fractions by Cassagrande method with the modification by Prószyński (Mocek *et al*., 2022)	Samples of disturbed structure (four replicates)
3.	Particle density (PD)	Blake and Hartge, 1986	Samples of disturbed structure (four replicates)
4.	Bulk density (BD)	Mocek *et al.* (2022)	Metal cylinders of known volume (100 cm^3) – samples of undisturbed structure (eight replicates)
5.	Total porosity (TP)	Mocek *et al.* (2022)	$TP = (\frac{PD - BD}{PD})100$
6.	Total carbon content (TC)	After dry combustion acc. to PN-ISO 10694:2002 (Polish Soil Classification, 2019) Using a Vario Max elemental analyser	Samples of disturbed structure (four replicates) Measurement precision was better than 0.5%
7.	Maximum hygroscopic capacity (MH)	MH was determined in a vacuum chamber at 0.08 MPa with a potassium sulphate (K_2SO_4) saturated solution (Mocek *et al*., 2022)	Samples of disturbed structure (four replicates)
8.	Soil water potential (pF* 2.0; 3.7; 4.2)	Richards pressure chamber method (Klute, 1986)	Before analysis, the samples were protected against moisture loss. Samples of undisturbed structure (eight replicates)
9.	Total available water (TAW) and readily available water (RAW)	Based on pF determinations (Mocek *et al*., 2022)	TAW = pF 2.0 – pF 4.2 RAW = pF 2.0 – pF 3.7

*pF – potential force.

(LSDs) were also estimated at a significance level of $\alpha = 0.05$. The relationships between the observed properties were assessed based on Pearson's correlation coefficients using an FCORRELATION procedure in GenStat 23. The results were also analysed using multivariate methods. A principal component analysis was applied to present a multi-trait assessment of the similarity of the tested tillage-cover crop combined in fewer dimensions with minimal information loss (Rencher, 1992). All analyses were conducted using the GenStat 23 statistical software package.

3. RESULTS AND DISCUSSION

3.1. Preliminary statistical analysis

The empirical distribution of all characteristics followed a normal distribution. The results of the MANOVA indicated that both factors (tillage: Wilk's $\lambda = 0.023603$; $F = 3.26$; $p < 0.0001$; cover crop: Wilk's $\lambda = 0.002169$; $F = 26.05$; $p < 0.0001$) and their interaction (Wilk's $\lambda = 0.000995$; $F = 3.21$; $p < 0.0001$) were significantly different for all 11 properties. ANOVA indicated that the main effects of cover crop were significant for all studied properties (Table 4).

Table 4. Mean squares from the analysis of variance for observed properties

Source of variation	Cover crop variant	Tillage method	Cover crop variant × tillage method	Residual
Degrees of freedom	2	3	6	60
TC	9.37754***	0.14885**	0.56652***	0.03111
PD	0.00251667***	0.00008333	0.00012778*	0.00005167
BD	0.050422***	0.017407***	0.012935***	0.001083
TP	58.634***	25.556***	19.142***	1.502
pF 2.0	32.8564***	7.3888***	3.9555***	0.5388
pF 2.5	6.4152***	1.7888**	2.4377***	0.3653
pF 3.7	3.5552***	2.8302***	2.6712***	0.4403
pF 4.2	2.4867**	1.8188**	1.5735***	0.3186
pF 4.5	2.13236***	1.25338***	0.47729***	0.09701
RAW	18.9431***	1.2418	1.7002	0.7575
TAW	38.5065***	2.8673*	2.687*	0.8267

*p<0.05, **p<0.01, ***p<0.001. TC – total carbon, PD – particle density, BD – bulk density, TP – total porosity, RAW – readily available water, TAW – total available water.

Tillage was statistically significant for all properties except particle density and RAW. The cover crop-tillage interaction was statistically significant for all properties except RAW (Table 4).

The influence of the experimental factors on soil texture was not examined. However, the texture analysis was a necessary condition to confirm the textural uniformity derived from the agricultural soil map. The differences in texture between individual combinations were small and did not exceed the limits of soil textural classes. The sand content was in the range of 75-76%, silt 19-21%, and clay 4-5%, so all analysed combinations were classed in line with USDA as Loamy Sand (Soil Survey Division Staff, 1993). Texture was thus highly uniform among all combinations, so the key condition of homogeneity required for field tests was met.

3.2. Total carbon content

The TC content in the tested combinations ranged from 10.1 g kg $^{-1}$ (WCC-ST) to 11.8 g kg^{-1} (WM-ST, Table 5). The $CaCO_3$ content was 0%, so it did not affect TC. The cover crop factor modified this property (Table 4). The average TC content in the variants was 10.4 g kg^{-1} without cover crop, 11.4 g kg^{-1} in the pea variants, and 11.6 g kg^{-1} in the white mustard variants, and these values differed from each other (Table 5). This indicates that the cover crops used slightly increased the TC content. A beneficial effect of field pea cover crops on TC content was also reported by Haruna *et al.* (2017). In practical terms, the increase in TC found in this study appears small. Perhaps if the assessed cover crops were applied for many years, the increase would be greater and it would have a more measurably practical implication. This supposition is based on long-term studies conducted by other authors showing that cultivation of

Table 5. Total carbon content and selected physical properties of examined plots

Cover crop variant	Tillage method	Total carbon content	Particle density	Bulk density	Total porosity (%)
		(g kg^{-1})	(Mg m^{-3})		
WCC	CT	10.9f	2.64a	1.67bc	36.7cd
	RT	10.2g	2.64a	1.63de	38.4b
	ST	10.1g	2.64a	1.74a	34.2e
	NT	10.3g	2.64a	1.65bcd	37.5bc
FP	CT	11.1e	2.63b	1.56g	40.6a
	RT	11.6ab	2.62c	1.64cde	37.3bc
	ST	11.4cd	2.62c	1.61ef	38.5b
	NT	11.5bc	2.62c	1.69b	35.6de
WM	CT	11.6ab	2.63b	1.55g	41.1a
	RT	11.7ab	2.62c	1.55g	40.7a
	ST	11.8a	2.63b	1.58fg	40.1a
	NT	11.2de	2.63b	1.65cde	37.3bc
Mean for cover crop variant	WCC	10.4c	2.64a	1.67a	36.7c
	FP	11.4b	2.62b	1.63b	38,0b
	WM	11.6a	2.63b	1.58c	39.8a
Mean for tillage method	CT	11.3a	2.63a	1.59b	39.4a
	RT	11.2a	2.63a	1.61b	38.80a
	ST	11.1b	2.63a	1.64a	37.6b
	NT	11.0b	2.63a	1.66a	36.8b

α = 0.05/values marked with the same letters do not differ significantly. Explanation as in Table 1.

cover crops beneficially affects TC in silty loam textured soil (Blanco-Canqiu *et al*., 2011). Olson *et al*. (2010) also share their observations on the impact of cover crops on TC content, claiming that it depends on such factors as the type of cover crop, soil type, and climate; this finding was confirmed by, among others, Haruna *et al*. (2017) in silty loamy textured soil and Ding *et al*. (2006) in sandy loam textured soil. Other authors (Rankoth *et al*., 2019) note the role of microbial biomass here. A report by Haruna *et al*. (2020) draws interesting conclusions. The authors claim that, in the initial period after the introduction of cover crops, the growth of TC is inhibited by an increase in microbiological activity and mineralisation of organic matter. Over time, this activity decreases, allowing TC to increase.

The tillage system had a weaker influence on TC than did the CC factor (Table 4). It ranged from 11.0 g kg^{-1} (no-till) to 11.3 g kg^{-1} (conventional tillage; Table 5). It was surprising to find that the use of the simplifications (RT, ST, NT) did not raise the content of TC, but there are also such reports in the literature (Mijangos *et al*., 2006). Different conclusions are provided in the paper by Thomas *et al*. (2007), which examined the influence of three tillage systems (conventional tillage, reduced tillage, and no-till) on Luvisols and found that the TC contents in the 0-30 cm layer were similar under CT and RT systems and considerably higher under NT. In a broader perspective, the issue was studied by Aziz *et al*. (2013), who analysed the impact of no-till and conventional tillage on, among other things, total carbon (TC), active carbon (AC), particulate organic matter (POM), and microbiological carbon (C_{mic}). They found improvements in all four parameters at all tested depths in response to no-till. A beneficial effect of NT on TC content has also been noted by Balota *et al*. (2014). These authors believe that, by avoiding the destructive impact on soil aggregates associated with ploughing, NT protects organic matter against mineralisation. Other authors draw attention to an important aspect of increasing TC content, *i.e*. increased microbiological activity and, consequently, increased stability of aggregates and improved sandy loam textured soil quality (Lagomarsino *et al*., 2012).

3.3. Basic physical properties

3.3.1. Particle density

The particle density in the tested experimental combinations ranged from 2.62 to 2.64 Mg m^{-3} (Table 5). In our opinion, the analysis of variance in this trait should be compared against the TC content results. The dependence of PD on organic matter content has been repeatedly confirmed in studies. The authors of the above-mentioned reports unanimously report that particle density decreases with increasing organic matter content (Sollins *et al*., 2009). A similar trend was also noted in the results obtained in this study, with the correlation of these parameters at -0.85 (Table 6). This property was modified by the cover crop factor (Table 4). On average, PD was 2.62 Mg m^{-3} in the plots where pea was grown, slightly and statistically insignificantly higher (2.63 Mg m^{-3}) in the plots with mustard, and statistically significantly highest (2.64 Mg m^{-3}) in the factors without cover crop (Table 5). The tillage system did not affect PD (Table 4).

3.3.2. Soil bulk density and total porosity

Soil bulk density and total porosity are important from an agrotechnical point of view, while also calling the attention of agricultural practitioners. Soil density in the analysed experimental combinations ranged from 1.55 Mg m^{-3} (WM-CT, WM-RT) to 1.74 Mg m^{-3} (WCC-ST). However, the total porosity ranged from 34.2 (WCC-ST variant) to 41.1% v. (WM-CT). Both properties were strongly modified by the cover crop factor (Table 4). The analysis of the

Table 6. Correlation coefficients between observed properties

Trait										
TC	1									
PD	-0.85***	1								
BD	-0.56	0.39	1							
TP	0.49	-0.30	-0.99***	1						
pF 2.0	0.75***	-0.51	-0.79**	0.77**	1					
pF 2.5	0.55	-0.35	-0.91***	0.91***	0.91***	1				
pF 3,7	0.47	-0.35	-0.68*	0.67*	0.77**	0.82**	1			
pF 4.2	0.12	-0.13	-0.37	0.37	0.32	0.47	0.74**	1		
pF 4.5	0.52	-0.55	-0.32	0.26	0.51	0.41	0.57	0.66*	1	
RAW	0.74**	-0.47	-0.63*	0.60*	0.87***	0.69*	0.35	-0.11	0.31	1
TAW	0.73**	-0.48	-0.65*	0.64*	0.91***	0.74**	0.48	-0.11	0.25	0.96***
	TC	PD	BD	TP	pF 2.0	pF 2.5	pF 3.7	pF 4.2	pF 4.5	RAW

*p<0.05, **p<0.01, ***p<0.001. Explanation as in Table 4.

obtained averages for this factor showed the highest bulk density (1.67 Mg m^{-3}) in the combinations without cover crop and the lowest value (1.58 Mg m^{-3}) in the combinations where white mustard was grown (Table 5). In terms of the influence of the cover crop type, it was found that TP was statistically significantly lowest (on average 36.7% v.) in the variants without cover crop and had the highest value (39.8% v.) in the white mustard variants. These changes indicate a positive change, a trend, and therefore the advisability of sowing the cover crops in question. With regard to the statistically significant but small impact of this factor on TC content, the mechanism behind this change is hard to discern. Based on the reports by Jassogne (2008), we suspect that the decrease in density was the result of an increase in root density and, consequently, in root spaces. Chaudhari *et al*. (2013) similarly note that biopores left behind by plant roots increase soil porosity, and this also reduces the mass/volume ratio of soils. A beneficial effect of the use of cover crops on bulk density and total porosity in sandy textured soil was noted by Dopka *et al.* (2013). The authors report a decrease in BD as a result of the use of cover crops of yellow lupine, blue phacelia, and white mustard, compared to plots where no cover crop was grown. The authors tested this property at two depths: 0-5 and 5-10 cm. In both cases, the lowest BD was found in combinations with white mustard, and after a three-year experiment, these changes were negligible and at a similar level as in our paper. The authors claim that this change was influenced by the supply of organic matter from the cover crop. Introducing a pea cover crop was found to have a slight effect on BD by Haruna *et al*. (2017), but no effect was reported by Cercioglu *et al*. (2018). Also, of interest are studies verifying the advisability of leaving crop residues in the field. The procedure is reported to be of minor importance by Sindelar *et al*. (2019) but of major importance by Singh *et al*. (2018). A pea cover crop has a positive effect on the physical properties of the soil when used on its own, but also when used in a mixture. This is the conclusion drawn by Ozturkmen *et al*. (2020). In a two-year experiment conducted on soil with low organic matter content, these authors examined the influence of common vetch + barley, common vetch + triticale, forage pea + barley, and forage pea + triticale mixtures on soil aggregate stability, total soil porosity, and soil bulk density. All these parameters were more favourable in the mixtures with pea than in the mixtures with common vetch.

The tillage method was also found to affect BD and TP, but less than the cover crop (Table 4). The bulk density was found to have the lowest value (1.59 Mg m^{-3}) in the combinations with conventional tillage (CT) and the highest level (1.66 Mg m^{-3}) in the combinations with no-till (NT). The factors with no-till (NT) were characterised by the lowest average total porosity (36.8% v.) and those with the highest values (39.4% v.) were conventional tillage (CT, Table 5). This tillage-dependent variation in BD and TP had statistical significance, but, likewise in the variation depending on the cover crop, it was small from an agricultural point of view. In our opinion, they should be interpreted as indicating the advisability of cultivation simplifications (RT, ST, NT) because they did not result in a real increase in density, while being economically more advantageous solutions (Šarauskis *et al*., 2020). Increased bulk density in loamy sand textured Luvisol due to the use of cultivation simplifications (RT, NT) was also noted by Włodek *et al*. (2012). The results reported by Kaczmarek *et al*. (2013) contradict the view that cultivation simplifications (NT) have a beneficial effect on BD and TP of loamy sandy textured soil. These authors conducted an interesting assessment of the impact on the level of basic physical properties and the availability of water to plants of a single treatment of conventional tillage on plots where no-till had been used for 12 years. Their study did not include a statistical analysis, but a higher density was noticeable in the plot of uninterrupted no-till. The authors point out that there are no practical negative consequences of using cultivation simplifications, and therefore they reach similar conclusions to those drawn from the present study. Afzalinia and Zabihi (2014) also assessed the impact of different cultivation systems on soil properties. The authors compared bulk density depending on the tillage method (ZT – zero tillage, RT – reduced tillage, CT – conventional tillage) and noticed that omitting all ploughing (ZT) resulted in increased BD compared to the RT and CT variants. They also noted that the lowest density was found in the CT variant. The authors explain the increase in density in ZT and its decrease in CT with the mechanical disturbance of the soil. Interesting conclusions are provided by an experiment conducted by Cudzik *et al*. (2011). They analysed the impact of three different cultivation systems: traditional (autumn discing, winter ploughing to a depth of 30 cm), simplified (autumn discing), and no-till (no agrotechnical treatments) on loamy sand textured soil properties in a 15-year experiment. In their analysis of the compactness of the soil (to a depth of 80 cm), the authors noted that, in the 0-30 cm layer, the conventionally ploughed soil had the lowest compactness. Below the depth of action of the plough, the compactness in the traditional system increased clearly, probably, as the authors claim, as a result of the appearance of a plough sole. The compactness in the surface layer (0-30 cm) was higher under reduced tillage than in the no-till system, and below this layer these values equalised and remained stable down to the bottom of the tested layer.

There are also opinions that reduced tillage, or even no-till, causes BD to decrease and TP to increase. This was found in a 24-year field experiment testing five cultivation systems: NT11 (11 years of continuous no-till), NT 24 (24 years of uninterrupted no-till), CT (24 years of uninterrupted conventional tillage with a heavy disc harrow to a depth of 0.15 m, followed by a light disc harrow to a depth of 0.08 m), MTC1 (annual secondary cultivation before winter tillage and NT before summer tillage), and MTC2 (secondary cultivation once every three years before winter cultivation and NT before summer cultivation; de Moraes *et al*., 2016). The authors analysed the impact of these techniques on bulk density, total porosity, macroporosity, and microporosity at three depths: 0-10, 10-20, and 20-30 cm. The experiment revealed an interesting variability. At the depth of 0-10 cm only, BD was larger and TP smaller in the NT system than in the CT system, while at the depth of 20-30 cm the inverse was true. At a depth of 10-20 cm, these differences were statistically insignificant. The authors attribute the higher density of the surface level to the lack of mechanical tillage. In turn, the authors concluded that the greater density of the 20-30 cm layer was attributable to a plough sole resulting from many years of ploughing to the same depth. Other authors attribute the lower density of deeper layers in NT systems to more intense root penetration and the associated appearance of post-root biopores (Soracco *et al*., 2012). An increase in density due to conventional tillage was also noted by Alhameid *et al*. (2017). During a four-year experiment, the authors compared selected soil properties, including BD. They found that BD in the 0-15 cm layer was higher under the CT system than under NT under both soybean and maize crops. BD was 1.24 Mg m^{-3} (NT) and 1.28 Mg m^{-3} (CT) for soybean and 1.23 Mg m^{-3} (NT) and 1.27 Mg m^{-3} (CT) for maize. Despite their statistical significance, these values appear to be negligible in the context of agricultural practice. The authors do not explain the mechanism of these changes, but they also report larger water-stable aggregates (WSA) in the NT system, which, in the context of the relationship between WSA and BD (greater WSA – lower BD, García-Orenes *et al*., 2005), allows us to see it as an explanation of the change.

The complexity of the influence of tillage methods on the physical properties of the sandy loam soil is noted by Gronle *et al*. (2015). In this context, they tested conventional and shallow ploughing. The results were inconsistent, as noted by the authors. During the two-year study period, in the first year they found an increase in BD as a result of the use of shallow ploughing, with a simultaneous decrease in air capacity. In the second year of the study, both properties were very similar and statistically insignificantly different between the two cultivation systems. The authors do not explain the mechanism of this variability, but refer to the research carried out by Riley and Ekeberg (1998), who also noted that, over time, tillage depth ceases to affect physical properties.

In the context of the impact of cultivation simplifications on density, which may be expressed in both BD and penetration resistance, the observation reported by Li *et al*. (2020) is valuable. The authors conducted an extensive analysis of 264 publications focusing on this issue. On this basis, they conclude that most studies indicate greater soil compaction in NT systems compared to CT. In their opinion, the fastest increase in density occurs in the first six years after cessation of ploughing, and in later years these differences disappear. Li *et al*. (2020) explain that density equalises due to "rebounds of porosity" and increases in organic matter content, with the latter, according to many authors, being the main factor shaping BD (Heuscher *et al*., 2005; Luo *et al*., 2010). Li *et al*. (2020) also attribute the beneficial effect of NT on physical properties to the impact that the lack of ploughing may have on WSA, and thus also on BD. Based on a literature analysis, they explain it in terms of increased organic matter accumulation in the topsoil layer (Blanco-Canqui *et al*., 2009; Schmidt *et al*., 2018).

3.4. Water retention characteristics

In the context of agricultural practice, in addition to the properties already described, soil retention capabilities are of key importance, especially with regard to water available to plants. Many authors recognise their importance as a buffer protecting the soil environment against climate change (Abdallah *et al*., 2021). Other papers emphasise the possibility of increasing water retention capacity – especially water available to plants – by increasing organic matter content (Ankenbauer and Loheide, 2017). The modifying impact of conservation agriculture on pore-size distribution, pore continuity, and bio-porosity of sandy loam textured soil is also emphasised (Villarreal *et al*., 2020). This impact is mainly visible at surface levels (Blanco-Canqui and Ruis, 2018).

The field capacity (soil moisture at pF 2.0) was in the range of 18.6% v. (WCC-ST variant) to 23.7% v. (WM-CT variant). Soil moisture ranged from 12.2% v. (WCC-ST) to 14.9% v. (WM-CT) at pF 2.5, from 9.8% v. (WCC-ST) to 12.2% v. (WM-CT) at the refill point (RP; pF 3.7), from 5.1% v. (WCC-ST) to 7.2% v. (FP-CT) at the permanent wilting point (PWP) (pF 4.2), and from 2.1% v. (WCC-ST) to 3.6% v. (FP-RT) at pF 4.5 (Table 7). The cover crop factor modified all the soil moisture levels described above (Table 4). The analysis of the averages for the cover crop factor revealed that most of the lowest moisture content was found in the factors without cover crop, and most of the highest moisture contents were found in the variants with white mustard. At the tested potentials, most of the average soil moistures found in the WCC variant differed from those of the FP and WM variants. The exception to this pattern was soil moisture at PWP. The ranges of readily available water (RAW) and total available water (TAW) are agrotechnically important. RAW ranged from 8.3% v. (WCC-RT) to 11.5% v. (WM-CT), and TAW ranged from 13.2% v. (WCC-RT) to 17.2% v. (WM-CT). The average values for the cover crop factor were as follows: for RAW: 9.0% v (WCC), 9.4% v. (FP), and 10.7% v. (WM), and for TAW: 13.6% v. (WCC), 14.2% v (FP), and 16.1% v. (WM). Except the difference in RAW between WCC and FP, the above values differed statistically significantly, indicating

Table 7. Soil water potentials of examined plots

Cover crop variant	Tillage method	Moisture (% v.) at pF					RAW	TAW
		2.0	2.5	3.7	4.2	4.5	(% v.)	
WCC	CT	20.6de	13.3d	10.9cd	6.4bcd	3.1cde	9.7cde	14.2c-f
	RT	19.7f	13.5cd	11.4bc	6.5abcd	2.8e	8.3f	13.2f
	ST	18.6g	12.2e	9.8e	5.1f	2.1f	8.8ef	13.5ef
	NT	20.4ef	13.8bcd	11.0cd	6.7abc	3.2bcd	9.4de	13.7def
FP	CT	21.3cd	14.2bc	12.1ab	7.2a	3.2bc	9.2def	14.1c-f
	RT	20.7de	13.2d	10.8cd	6.1cde	3.6a	9.9b-e	14.6cd
	ST	20.4ef	13.6cd	11.0cd	6.7abc	3.2bcd	9.4de	13.7def
	NT	21.2de	13.5cd	12.0ab	6.9ab	3.5ab	9.2def	14.3cde
WM	CT	23.7a	14.9a	12.2a	6.5abcd	3.4abc	11.5a	17.2a
	RT	22.2b	14.5ab	11.4bc	5.8ef	2.9de	10.8ab	16.4ab
	ST	22.1bc	14.4ab	11.5abc	6.2b-e	2.8de	10.6abc	15.9b
	NT	20.7de	13.3d	10.6de	5.9de	3.1cde	10.1bcd	14.8c
Mean for cover crop variant	WCC	19.8c	13.2c	10.8b	6.2b	2.8c	9.0b	13.6c
	FP	20.9b	13.6b	11.5a	6.7a	3.4a	9.4b	14.2b
	WM	22.2a	14.2a	11.5a	6.1b	3.0b	10.7a	16.1a
Mean for tillage method	CT	21.9a	14.1a	11.8a	6.7a	3.3a	10.1a	15.2a
	RT	20.9b	13.7b	11.2b	6.1bc	3.1a	9.7ab	14.8ab
	ST	20.4c	13.4b	10.8c	6.0c	2.7b	9.5b	14.3b
	NT	20.8bc	13.5b	11.2b	6.5ab	3.2a	9.5b	14.3b

$\alpha = 0.05$/values marked with the same letters do not differ significantly. Explanations as in Table 1.

that the effect of cover crops was beneficial, albeit slight (as in the cases of TC and physical properties). The soil moisture at the individual pF potentials described above usually did not correlate with TC, with the exception of soil moisture at field capacity (FC), where the correlation was moderate and amounted to 0.75 (Table 6). For RAW and TAW, the correlations with TC were moderate, at 0.74 and 0.73, respectively. Most soil moistures at individual potentials as well as RAW and TAW correlated negatively with BD and positively with TP (Table 6).

The beneficial effect that a forage intercrop in a mixture with barley and triticale had on retention capacity is emphasised by the afore-cited study by Ozturkmen *et al.* (2020). As with physical properties, the effect of these mixtures was more favourable than that of common vetch–barley and common vetch-triticale mixtures. An increase in water content at potentials 0, -33, -100, and -300 kPa due to the use of pea cover crops was found by Haruna *et al.* (2017), who associated it with increased TC content. More broadly, the beneficial effect of using various cover crops on retention capacity is explained by Basche *et al.* (2016). These authors noted that, in 0-15- and 15-30 cm layers, the use of CC increased plant available water by 21 and 22%, respectively. They found that the beneficial effect of CC could be due to the increase in porosity, organic matter content, and aggregate stability. A similar opinion is expressed by Villamil *et al.* (2006). In our analysis, the use of cover crops increased plant available water to a decidedly lesser extent than in the cited article by Bashe *et al.* (2016). However, this last study lasted over a dozen years, which is much longer, but the positive trend noted in our research may continue in the coming years. A similar observation to that reported by Bashe and colleagues is made by Wood *et al.* (2021), who claim that the beneficial effect of organic matter on retention capacity becomes visible only after considerable changes in the organic matter content.

Praharaj and Maitra (2020) report on the beneficial effects of legume crops, associating them with improved structural stability and porosity. An interesting opinion on the impact of an increase in organic matter content at FC and PWP is expressed by Lal (2020). The author claims that, in most studies, an increase in OM content only increases FC and does not increase PWP. However, Lal (2020) also notes that in some soils the impact of organic matter content on FC and PWP is similar, and therefore an increase in organic matter content is not associated with an increase in plant available water. The mechanism behind the beneficial effect of OM on retention capacity most likely results from the improved distribution of differential porosity. This claim is made in a paper by Panagea *et al.* (2021). They also note that it is greater than the benefit resulting from the higher water holding capacity of organic matter as an element of the solid phase.

The second tested factor, tillage method, modified the above-mentioned soil moistures at pF points statistically significantly, but its effect was weaker (Table 4). The highest contents of all analysed moistures were noticeable in the CT variant and for pF 2.0, 2.5, 3.7, 4.2, and 4.5 they were 21.9, 14.1, 11.8, 6.7 and 3.3% v., respectively. The lowest soil moisture values were recorded in the ST variant and were as follows: 20.4, 13.4, 10.8, 6.0, and 2.7% v. (Table 7). The average RAW and TAW values for the cultivation method factor were 9.5 (NT, ST), 9.7 (RT), and 10.1 (CT) and 14.3 (NT, ST), 14.8 (RT), and 15.2% (CT), respectively. Only the differences between CT and ST and between CT and NT were statistically significant. Among the simplified forms of cultivation, they were statistically insignificant.

At the current stage of research, the results obtained suggest that the use of cultivation simplifications may have unfavourable impacts on the soil retention capacity. However, as in the case of physical properties, these differences are small in terms of practical implications. An interesting analysis of literature reports was conducted by Abdallah *et al.* (2021). The authors found that most short-term (<10-yr) studies report a decrease in porosity in response to the implementation of simplified cultivation, and only a few papers (Patra *et al.*, 2019) indicate the opposite changes. Long-term studies are also inconclusive. Lipiec *et al.* (2006) conclude an unfavourable impact of 18 years of simplified cultivation on the retention capacity of silt loam soil. De Moraes *et al.* (2016) are of the opposite opinion, as their 24-year study found a beneficial effect of simplified cultivation on the retention capacity of clay soil. Probably, the differences in these results were due to differences between the soils studied by the two teams. The literature also contains reports of cultivation methods having no statistically significant impact on retention capacity. These include both short-term (Vogeler *et al.*, 2009) and long-term studies (Blanco-Canqui *et al.*, 2017). When analysing the issue of the impact of conservation practices on retention capacity, it is also worth considering reports in the context of the depths at which the impact of the simplified cultivation method is seen. Sometimes a positive impact is visible in the surface layer only (Himmelbauer *et al.*, 2012; So *et al.*, 2009). In terms of the beneficial impact of conservation agriculture on retention capacity, the relationship with organic matter content is also puzzling. It is widely accepted that an increase in organic matter content induces an increase in the water content available to plants. Such reports are shared by, among others, So *et al.* (2009). There is also literature verifying these findings (Minasny and McBratney, 2018). The above-mentioned authors conducted an extensive literature analysis (60 publications, 50 000 measurements from all over the world) to conclude that an increase in OC content of 10 kg^{-1} resulted in an increase in available water of 0.7-2.0 mm. They claim that, "compared with reported annual rates of carbon sequestration after the adoption of conservation agricultural systems, the effect on soil available water is negligible". Thus, arguments for sequestering carbon to increase water storage are questionable. The authors also link the influence of organic matter on soil available water with texture, claiming that it is the greatest in sandy soils, smaller in loam soils, and the smallest in clay soils. Based on other literature reports (Haruna *et al.*, 2017), we assume that the improvement in soils in which retention capacity improved despite the lack of a clear increase in organic matter content was due to the presence of post-root soil pores.

Taking into account all the above reports, a complex picture of the impact of conservation tillage on retention capacity emerges. Attention is drawn to the positive impact of the use of cover crops and the lack of or a minimally negative impact observed in our assessments of the variability caused by cultivation simplifications. In the case of retention capacity, the statistically significant differences were too small to be considered noteworthy from a practical point of view. This issue is very complex, and the final impact of cultivation simplifications is a function of not only anthropogenic factors (*i.e.*, the type of cultivation used and its duration) but also soil factors (*i.e.*, primarily texture).

The results were also compiled multidimensionally. The effect of the combinations of the cover crop variant and the tillage method on the values of all eleven properties taken together was evaluated by principal component analysis. The results of this analysis are shown in Fig. 1. The first and second principal components explained 77.71% and 13.38% of the total multitrait variability, respectively. The combinations of the differentiating factors considered grouped into three clusters.

3.5. Wheat yield variability – preliminary data

In the research project, the variability of wheat yield was also analysed. The obtained data are analysed using statistical tests. Preliminary information shows that the use

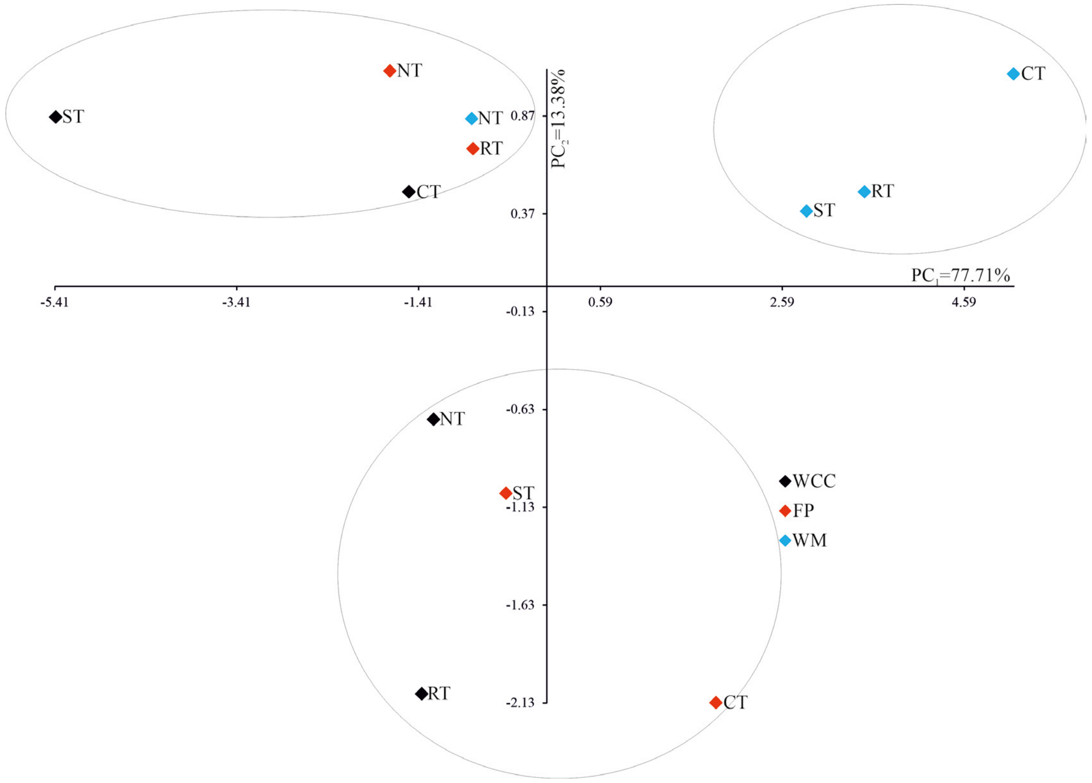

Fig. 1. Distribution of combinations of cover crop variant and tillage method in the arrangement of the first two principal components.

of cover crops had a positive effect and the use of cultivation simplifications had a negative impact on the wheat yield. Taking this feature into account, WM-CT seems to be the most favourable cultivation system variant. Detailed data will be presented in a separate article.

4. CONCLUSIONS

1. The experimental factors influenced the tested properties, and the sowing of cover crops had a greater impact than did the variations in the tillage method.
2. The tested factors modified total carbon content. The use of cover crops increased total carbon content, whereas simplified cultivation decreased this parameter.
3. The variants with cover crops were characterised by lower soil density and higher porosity than the variants without. Cultivation simplifications resulted in deterioration in these parameters.
4. The use of cover crops slightly improved retention capacity, whereas simplified cultivation slightly reduced its level.
5. From an agricultural point of view, only the white mustard - conventional plough tillage variant was characterised by beneficial values of the majority of the soil properties studied.

Conflicts of Interest: The Authors do not declare any conflict of interest.

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