





Effects of tillage, cover crop management and nitrogen fertilisation on soil physical properties in spring barley

Roman Waclawowicz¹^{*}, Magdalena Giemza², Piotr Kuc¹, Anna Lehmann-Skoczylas¹,
Dorota Gawęda³, Sylwia Andruszczak³

¹Institute of Agroecology and Plant Production, Wrocław University of Environmental and Life Sciences, 24A Grunwaldzki Sq., 50-363 Wrocław, Poland

²Research and Development, DLF Beet Seed ApS, Højbygårdvej 31, 4960 Holeby, Denmark

³Department of Herbology and Plant Cultivation Techniques, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland

Received April 21, 2026; accepted June 8, 2026

Abstract. Agricultural intensification often degrades soil physical properties; therefore, this study evaluated the effects of tillage, white mustard cover crop management, and nitrogen fertilisation on selected soil physical properties in spring barley. A three-year split-plot field experiment on Haplic Chernozem included four tillage and cover crop management treatments (conventional ploughing without a cover crop and conventional, reduced, and no-tillage with a cover crop) and three nitrogen rates (40, 80, 120 kg N ha⁻¹). Soil moisture, total and capillary porosity, penetration resistance, and aggregate stability were measured at two dates and in two soil layers. Experimental effects were assessed using analysis of variance, while relationships among properties were examined by correlation and principal component analysis (PCA). Tillage and cover crop management was the main factor differentiating soil physical properties, whereas nitrogen effects were limited. No-tillage increased penetration resistance and reduced porosity early in the season, while reduced and no-tillage treatments enhanced aggregate stability later in the season. Cover crop effects were seasonal, initially destabilising and later improving aggregate stability. PCA indicated that the relationship between penetration resistance and porosity was the principal mechanism differentiating tillage and cover crop management treatments, and that treatments including a cover crop modified the interrelationships among penetration resistance, porosity, and aggregate stability, shaping the seasonal dynamics of soil physical functioning.

Keywords: tillage, cover crop management, nitrogen fertilisation, soil physical properties, aggregate stability, spring barley

1. INTRODUCTION

The progressive intensification of agricultural production, encompassing simplified crop rotations and a high frequency of tillage operations, leads to the deterioration of the physical properties of cultivated soils, consequently disrupting the equilibrium of the entire ecosystem. Soil compaction and reduced porosity are among the principal factors limiting soil productivity and resilience to water deficits and extreme precipitation events (Hamza and Anderson, 2005). Increased penetration resistance restricts root development and water infiltration and may also indirectly affect soil structure formation (Lipiec and Hatano, 2003; Zhang *et al.*, 2024; Hamza *et al.*, 2025).

Tillage is a key factor shaping soil physical conditions. Conventional plough-based tillage, despite its numerous agronomic advantages, may lead to excessive loosening of the topsoil layer and compaction of the underlying layers. An alternative is provided by reduced and no-tillage treatments, which minimise mechanical disturbance of the soil and favour the preservation of its structure (Wang *et al.*, 2024). However, the effects of these systems on soil physical properties are variable and depend on site conditions and crop residue management (Rocco *et al.*, 2024).

© 2026 Authors. Published by Institute of Agrophysics, Polish Academy of Sciences. This is an open access article licensed under the Creative Commons Attribution 4.0 License (CC BY 4.0)

*Corresponding author e-mail: roman.waclawowicz@upwr.edu.pl



Cover crops can substantially modify the impact of tillage on the soil environment. Their inclusion in crop rotation enhances aggregate stability, improves soil structural parameters and may increase water infiltration and soil water retention (Blanco-Canqui and Ruis, 2018; Nouri *et al.*, 2019; Gabriel *et al.*, 2019; Çerçioğlu *et al.*, 2019; Yan and Arthur, 2025). Long-term experiments also indicate that cover crops may promote organic carbon accumulation and strengthen soil structural resilience (Pearsons *et al.*, 2025; Dai *et al.*, 2025). Similar effects have also been reported under Central European conditions (Gajewski *et al.*, 2025).

The effect of nitrogen fertilisation on soil physical properties is most commonly indirect, arising from changes in root system development and the quantity of crop residues incorporated into the soil (Bai *et al.*, 2021). It is generally weaker than the effects of tillage methods and cover crop management, although it may influence, among other processes, soil aggregation (Six *et al.*, 2004; Piazza, 2020).

Previous research has mostly focused on individual agronomic factors and less frequently on their combined effects. Knowledge remains limited regarding the relationships between penetration resistance, porosity, and aggregate stability, particularly under the combined influence of tillage methods, cover crop biomass management, and nitrogen rates. These relationships are rarely analysed using multivariate methods, which enable a comprehensive assessment of interdependent changes in soil physical properties (Schmidt *et al.*, 2018; Gajewski *et al.*, 2025). Therefore, the added value of the present study lies in the integrated assessment of seasonal changes in soil physical properties under combined tillage, cover crop management and nitrogen rates.

This study aimed to evaluate the effects of tillage methods combined with white mustard (*Sinapis alba* L.) stubble cover crop management and nitrogen rates on selected soil physical properties in spring barley (*Hordeum vulgare* L.). We hypothesised that the tillage and cover crop management would be the dominant factors shaping the interrelationships among soil moisture, penetration resistance, porosity, and aggregate stability. Further, we assumed that the beneficial effects of the cover crop would be more pronounced at later developmental stages of the crop, whereas the effects of nitrogen fertilisation would be weaker.

2. MATERIALS AND METHODS

2.1. Experimental site and soil conditions

The field experiment was conducted at the Research and Education Station in Swojczyce (51°07'N, 17°08'E), of the Wrocław University of Environmental and Life Sciences, over a three-year research cycle (2010-2012). The experiment was established on Haplic Chernozem according to the World Reference Base for Soil Resources

(IUSS Working Group WRB, 2022), developed from light loam overlying medium loam, underlain by light loam, and classified as soil quality class IIIa, good wheat complex. Soil pH (in KCl) in the plough layer was 5.7. The soil in the plough layer was characterised by a total nitrogen content of 1.2 g kg⁻¹, available phosphorus content of 212 mg kg⁻¹ expressed as P₂O₅, and available potassium content of 169 mg kg⁻¹ expressed as K₂O.

2.2. Experimental layout and design

The experiment was set up as a two-factor split-plot design in randomised complete blocks with three replications. The area of a single sub-plot was 27.5 m². The experiment comprised four tillage and cover crop management treatments and three nitrogen rates (Table 1).

2.3. Tillage and cover crop management

The first experimental factor comprised tillage methods combined with the management of a white mustard (*Sinapis alba* L.) stubble cover crop. The investigated treatments differed in the intensity of mechanical soil disturbance and in the method of cover crop incorporation. After harvest of the preceding crop (spring wheat), straw was chopped and left on the soil surface. To accelerate its mineralisation, nitrogen was applied at a rate of 50 kg ha⁻¹. Straw management varied depending on the cultivation treatments. In the CT and CTcc treatments, straw was shallowly ploughed to a depth of 12 cm using a stubble plough, whereas in RTcc it was mixed into the soil using a stubble cultivator to a depth of 8-10 cm. The white mustard stubble cover crop (*cv.* Bardena) was sown immediately after post-harvest tillage at a seeding rate of 20 kg ha⁻¹. In the CTcc and RTcc treatments, sowing was performed using a conventional seed drill, whereas in NTcc direct drilling was applied. The depth of pre-winter ploughing was 20 cm in the CT treatment and 15 cm in the CTcc treatment, where this operation also served to incorporate cover crop biomass. In the RTcc and NTcc treatments, the cover crop was left on the soil surface over the autumn-winter period as mulch. In spring, white

Table 1. Experimental design of the field study

Treatment	Description
	Tillage and cover crop management
CT	Conventional tillage (control, without cover crop)
CTcc	Conventional tillage with cover crop
RTcc	Reduced tillage with cover crop
NTcc	No-tillage with cover crop
	Nitrogen rate (kg N ha ⁻¹)
N1	Single application 40
N2	Split application 80 (40 + 40)
N3	Split application 120 (40 + 50 + 30)

mustard biomass in the RTec treatment was incorporated into the soil using a rigid-tine cultivator to a depth of 10 cm, whereas in the NTec treatment a non-selective glyphosate-based herbicide (Roundup Energy 450 SL) was applied at a rate of 2.5 l ha⁻¹.

2.4. Fertilisation

Nitrogen was applied as ammonium nitrate (32% N) at rates of 40, 80, and 120 kg N ha⁻¹. For N1, the entire dose was applied before sowing; for N2, the dose was split between pre-sowing and stem elongation (BBCH 30-32); for N3, it was applied in three splits: before sowing, at stem elongation (BBCH 30-32), and at heading (BBCH 51-55). Potassium was applied uniformly across all treatments in spring before sowing as potassium chloride (60% K₂O) at a rate of 30 kg K₂O ha⁻¹. Phosphorus fertilisation was not applied owing to the very high available phosphorus content in the soil (212 mg kg⁻¹). All other agronomic operations followed standard practices for spring barley (*Hordeum vulgare* L. cv. Mercada).

2.5. Soil physical property measurements

Soil physical properties were determined at two dates during the growing season: in spring at the tillering stage (BBCH 21-23) and in summer at full maturity of spring barley (BBCH 89). Volumetric soil moisture and total and capillary porosities were determined in the 5-10 and 15-20 cm layers using 100 cm³ Kopecky cylinders on undisturbed soil cores (Blake and Hartge, 1986; Spasić *et al.*, 2023). Two subsamples were collected per experimental plot and averaged to obtain a single representative value. Soil penetration resistance was measured in the 0-20 cm layer at 10 cm intervals using a dynamic cone penetrometer constructed according to the design described by Herrick and Jones (2002), with five measurements taken per plot. The obtained values were averaged to yield a single value per plot for statistical analysis. The fractional composition of soil aggregates and their water stability were determined in the 0-10 and 10-20 cm layers by dry and wet sieving using a modified Bakhsheyev-type wet-sieving apparatus (Kemper and Rosenau, 1986; Mocek, 2020). Analyses were performed on a single sample collected from each experimental plot. The mean weight diameter of water-stable aggregates (MWD_w) was calculated as the sum of the products of the mass fraction of each aggregate size class and its mean diameter. The water stability index (WSI) was calculated as (MWD_w/MWD_d) × 100, where MWD_w and MWD_d are the mean weight diameters obtained by wet and dry sieving, respectively.

2.6. Statistical analysis

Normality and homogeneity of variance assumptions were verified using the Shapiro-Wilk and Levene tests, respectively. Analysis of variance (ANOVA) was performed according to the split-plot design, in which tillage and cover

crop management was assigned to the main plots and nitrogen rate to the sub-plots. This approach allowed the hierarchical structure of the experiment and the appropriate error terms for both factors to be taken into account. Tillage and cover crop management (T) and nitrogen rate (N) were treated as fixed factors, whereas year (Y) and block nested within year were treated as random factors. The model included the main effects of T, N, their interaction (T × N), year (Y), block(year), and the interactions Y × T and Y × N. Significant Y × T interactions were detected for selected variables, whereas Y × N interactions were not statistically significant. Since no crossover interactions were observed (the ranking of the tillage and cover crop management treatments remained stable in consecutive years), the results are presented as three-year means (2010-2012). The presented values represent means calculated across three experimental years and three field replications (n = 9). Values in the tables are presented as means ± standard deviation (SD). Differences between means were assessed using Tukey's test at p ≤ 0.05.

Relationships among soil physical properties were evaluated using Pearson's correlation coefficients (r), calculated separately for each measurement date and soil layer. Pearson's correlation was appropriate because the data met the assumptions of normality and the analysis aimed to assess linear relationships among the investigated properties. The analyses were performed on data averaged across years, with three field replications retained for each treatment combination. The number of observations was n = 12 for spring measurements (BBCH 21-23, factor T) and n = 36 for summer measurements (BBCH 89, factors T × N). The results are presented as heat maps with correlation coefficient values and significance levels (*p < 0.05, **p < 0.01, and ***p < 0.001).

Principal component analysis (PCA) was applied to reduce the dimensionality of the dataset and to identify the main gradients explaining multivariate differentiation of soil physical properties among treatments. Due to differences in units and scales, the analysis was performed on a correlation matrix using standardised variables. PCA was conducted on the same dataset as the correlation analysis (n = 12 for spring measurements and n = 36 for summer measurements). The analysis was performed separately for each measurement date and soil layer, and the number of significant components was determined according to Kaiser's criterion (eigenvalues > 1). The results are presented as biplots of variables and experimental treatments in the space of the first two principal components. All statistical analyses were performed using Statistica 13 (StatSoft Inc., Tulsa, OK, USA).

Table 2. Soil penetration resistance (MPa)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
0-10	CT	3.53±1.17bc	3.70±1.51	4.05±1.46	3.61±1.16	3.79±1.35b
	CTcc	3.44±1.31c	3.65±1.05	3.70±1.18	3.91±1.08	3.76±1.07b
	RTcc	4.63±2.69b	3.69±1.00	3.69±1.04	3.62±1.17	3.67±1.03b
	NTcc	10.23±4.22a	5.49±1.73	5.34±1.58	5.44±1.52	5.43±1.55a
	Mean		4.14±1.52	4.20±1.45	4.15±1.42	–
10-20	CT	7.70±2.05bc	4.76±0.73	5.03±0.98	4.95±1.15	4.91±0.94c
	CTcc	7.32±2.18c	5.09±1.15	5.13±0.89	5.40±1.08	5.20±1.01c
	RTcc	9.98±3.75b	6.12±1.35	6.45±1.39	6.07±1.05	6.21±1.23b
	NTcc	13.96±5.93a	7.64±1.80	7.56±1.67	7.68±1.30	7.63±1.54a
	Mean		5.90±1.70	6.04±1.61	6.02±1.52	–

Values are means ± SD (n = 9; three experimental years × three field replications). CT – conventional tillage (control); CTcc – conventional tillage with stubble cover crop; RTcc – reduced tillage with stubble cover crop; NTcc – no-tillage with stubble cover crop. N1 – 40 kg N ha⁻¹; N2 – 80 kg N ha⁻¹; N3 – 120 kg N ha⁻¹. Means followed by different letters differ significantly (Tukey's HSD test, p ≤ 0.05). Where no letters are shown, no significant differences were detected.

Table 3. Total soil porosity (cm³ cm⁻³)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
5-10	CT	0.399±0.037a	0.310±0.023	0.304±0.016	0.324±0.029	0.312±0.024
	CTcc	0.372±0.035a	0.303±0.023	0.311±0.033	0.323±0.019	0.312±0.026
	RTcc	0.386±0.040a	0.304±0.026	0.306±0.017	0.310±0.024	0.307±0.022
	NTcc	0.302±0.013b	0.294±0.025	0.296±0.017	0.298±0.022	0.296±0.021
	Mean		0.303±0.024	0.304±0.022	0.314±0.025	–
15-20	CT	0.371±0.030a	0.306±0.009	0.310±0.018	0.315±0.020	0.310±0.016
	CTcc	0.356±0.036a	0.315±0.024	0.311±0.018	0.318±0.022	0.315±0.021
	RTcc	0.316±0.024b	0.297±0.027	0.298±0.021	0.297±0.021	0.297±0.022
	NTcc	0.321±0.023b	0.297±0.019	0.310±0.029	0.304±0.017	0.304±0.022
	Mean		0.304±0.022	0.307±0.022	0.308±0.021	–

Explanations as in Table 2.

3. RESULTS

Soil penetration resistance in the early growing season was significantly differentiated by tillage and cover crop management treatment in both analysed soil layers (Table 2). In the 0-10 cm layer, soil under no-tillage (NTcc) exhibited nearly three-fold higher penetration resistance than under conventional tillage (CT) and conventional tillage with cover crop (CTcc), and two-fold higher than under reduced tillage (RTcc). A similar pattern was maintained in the 10-20 cm layer, where penetration resistance values in NTcc were 81% higher than in CT. At full crop maturity, the highest penetration resistance values persisted in NTcc,

with less pronounced differentiation among the remaining treatments. Nitrogen fertilisation had no significant effect on the analysed trait.

A different pattern of changes was observed for total porosity compared with soil penetration resistance (Table 3). In the early growing season, in the 5-10 cm layer, a significant reduction in this parameter was recorded only under no-tillage (NTcc), while in the CT, CTcc, and RTcc treatments, porosity remained at a similar level. In the 15-20 cm layer, two groups were distinguished: higher total porosity values occurred in the CT and CTcc treatments, whereas values in RTcc and NTcc were, on average, 13% lower.

At full crop maturity, neither tillage and cover crop management nor nitrogen rate had a significant effect on the analysed trait.

Soil capillary porosity exhibited a similar pattern of changes to total porosity (Table 4). In the early growing season, in the 5-10 cm layer, the significantly lowest value of this parameter was recorded under no-tillage (NTcc), where it was 23% lower than in both the CT and RTcc treatments. In the 15-20 cm layer, two groups of treatments were distinguished: CT and CTcc were characterised by significantly higher capillary porosity than RTcc and NTcc. This pattern in the deeper layer persisted at full crop maturity, whereas in the shallower layer (5-10 cm) the differences between treatments diminished. Nitrogen fertilisation did not cause significant changes in soil capillary porosity.

Soil moisture exhibited a different pattern of changes compared with the previously analysed soil properties. In spring, it remained at a similar level regardless of the tillage and cover crop management treatment in both investigated layers (Table 5). A distinct differentiation became apparent only at full crop maturity in the 15-20 cm layer, with the highest soil moisture recorded under conventional tillage (CT), and subsequently decreasing progressively with increasing reduction in tillage intensity, reaching a value more than 10% lower under no-tillage (NTcc) than under CT. The effect of nitrogen fertilisation was again not statistically significant.

The mean weight diameter of water-stable aggregates (MWDw) exhibited pronounced seasonal variability (Table 6). During the spring period, in the 0-10 cm layer, the highest values were recorded under conventional tillage

Table 4. Capillary porosity of soil ($\text{cm}^3 \text{cm}^{-3}$)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
5-10	CT	0.323±0.029a	0.289±0.019	0.287±0.008	0.300±0.020	0.292±0.017
	CTcc	0.309±0.029a	0.288±0.017	0.295±0.017	0.300±0.021	0.294±0.018
	RTcc	0.323±0.034a	0.295±0.025	0.296±0.023	0.297±0.018	0.296±0.021
	NTcc	0.248±0.016b	0.291±0.039	0.276±0.020	0.283±0.018	0.283±0.024
	Mean		0.291±0.029	0.288±0.019	0.295±0.020	–
15-20	CT	0.316±0.027a	0.293±0.017	0.291±0.016	0.294±0.019	0.293±0.017a
	CTcc	0.308±0.030a	0.294±0.022	0.289±0.010	0.297±0.018	0.293±0.017a
	RTcc	0.273±0.017b	0.279±0.014	0.273±0.013	0.276±0.012	0.276±0.013b
	NTcc	0.273±0.021b	0.276±0.024	0.279±0.029	0.281±0.013	0.279±0.022b
	Mean		0.286±0.020	0.283±0.019	0.287±0.018	–

Explanations as in Table 2.

Table 5. Soil moisture ($\text{cm}^3 \text{cm}^{-3}$)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
5-10	CT	0.181±0.055	0.250±0.013	0.244±0.009	0.240±0.015	0.245±0.013
	CTcc	0.180±0.055	0.255±0.017	0.248±0.020	0.250±0.023	0.251±0.020
	RTcc	0.177±0.051	0.258±0.021	0.250±0.021	0.256±0.016	0.255±0.019
	NTcc	0.180±0.036	0.248±0.048	0.240±0.015	0.243±0.016	0.244±0.029
	Mean		0.253±0.027	0.246±0.017	0.247±0.018	–
15-20	CT	0.196±0.053	0.266±0.008	0.255±0.016	0.256±0.011	0.259±0.013a
	CTcc	0.209±0.056	0.254±0.020	0.254±0.015	0.249±0.015	0.252±0.016ab
	RTcc	0.195±0.044	0.246±0.005	0.239±0.007	0.244±0.006	0.243±0.007b
	NTcc	0.203±0.037	0.233±0.021	0.224±0.024	0.239±0.014	0.232±0.020c
	Mean		0.250±0.019	0.243±0.020	0.247±0.013	–

Explanations as in Table 2.

Table 6. Weighted mean diameter of soil aggregates (MWDw)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
0-10	CT	0.86±0.33a	0.72±0.10	0.67±0.09	0.67±0.12	0.68±0.10c
	CTcc	0.65±0.13c	0.84±0.27	0.72±0.16	0.85±0.16	0.80±0.25b
	RTcc	0.80±0.12ab	1.08±0.34	0.84±0.13	0.97±0.15	0.97±0.29a
	NTcc	0.67±0.15c	1.07±0.16	1.06±0.17	0.96±0.17	1.03±0.17a
	Mean		0.93±0.33a	0.82±0.20b	0.86±0.19b	–
10-20	CT	0.68±0.10	0.68±0.08	0.61±0.13	0.59±0.08	0.63±0.10b
	CTcc	0.57±0.07	0.78±0.19	0.70±0.20	0.67±0.14	0.72±0.17b
	RTcc	0.61±0.16	0.71±0.19	0.65±0.10	0.71±0.17	0.69±0.15b
	NTcc	0.63±0.10	0.87±0.13	0.97±0.17	0.86±0.14	0.90±0.15a
	Mean		0.76±0.16	0.74±0.20	0.71±0.16	–

Explanations as in Table 2.

Table 7. Water stability index of soil aggregates (WSI)

Soil layer (cm)	Treatment	Tillering	Full maturity			
			N1	N2	N3	Mean
0-10	CT	22.6±7.4a	18.6±3.40d	17.0±1.49d	16.3±3.07d	17.3±2.85c
	CTcc	18.3±4.01b	21.4±7.45bcd	17.8±5.18d	21.3±4.75bcd	20.2±7.19b
	RTcc	23.1±4.03a	28.8±5.16a	20.3±2.29cd	25.7±4.14ab	24.9±6.51a
	NTcc	18.1±4.16b	28.7±4.43a	28.1±5.10a	23.9±4.76abc	26.9±5.08a
	Mean		24.4±10.26a	20.8±5.79b	21.8±5.41b	–
10-20	CT	19.7±2.50a	16.5±2.31d	15.0±2.47d	14.6±2.09d	15.4±2.36c
	CTcc	15.1±2.48b	18.5±4.76bcd	16.7±5.53d	18.0±5.43cd	17.7±5.10b
	RTcc	16.6±4.44ab	19.0±7.18bcd	16.8±2.43d	17.4±3.11d	17.7±4.64b
	NTcc	18.5±3.17ab	23.3±3.89ab	27.9±5.43a	22.8±3.16bc	24.7±4.70a
	Mean		19.3±5.29	19.1±6.59	18.2±4.61	–

Explanations as in Table 2.

(CT), whereas soil under CTcc and NTcc was characterised by a significantly lower degree of aggregation. No significant differences between treatments were found in the 10-20 cm layer. At full crop maturity, a contrasting trend was observed: in the 0-10 cm layer, the highest MWDw values were obtained under RTcc and NTcc, which were 42 and 51% higher, respectively, than under conventional tillage (CT). The beneficial effect of no-tillage was also evident in the 10-20 cm layer, where MWDw was 43% higher than that under CT. In the surface layer, a significant effect of nitrogen fertilisation was also recorded: the highest MWDw values were obtained at the lowest nitrogen rate (N1), whereas higher nitrogen rates (N2 and N3) reduced this parameter by 8-12%.

The water stability index (WSI) exhibited a similar pattern of changes to MWDw (Table 7). In spring, the lowest WSI values in both soil layers were recorded under the treatment with an incorporated cover crop (CTcc), while in the 0-10 cm layer, they were additionally recorded under no-tillage (NTcc). At full crop maturity, these relationships were reversed; treatments with a cover crop (CTcc, RTcc, and NTcc) were characterised by higher aggregate water stability than conventional tillage (CT), with particularly beneficial effects recorded in RTcc and NTcc, where WSI values were 44 and 55% higher, respectively, than in CT. In the surface layer, the effect of nitrogen fertilisation also proved significant; the highest WSI values were obtained at

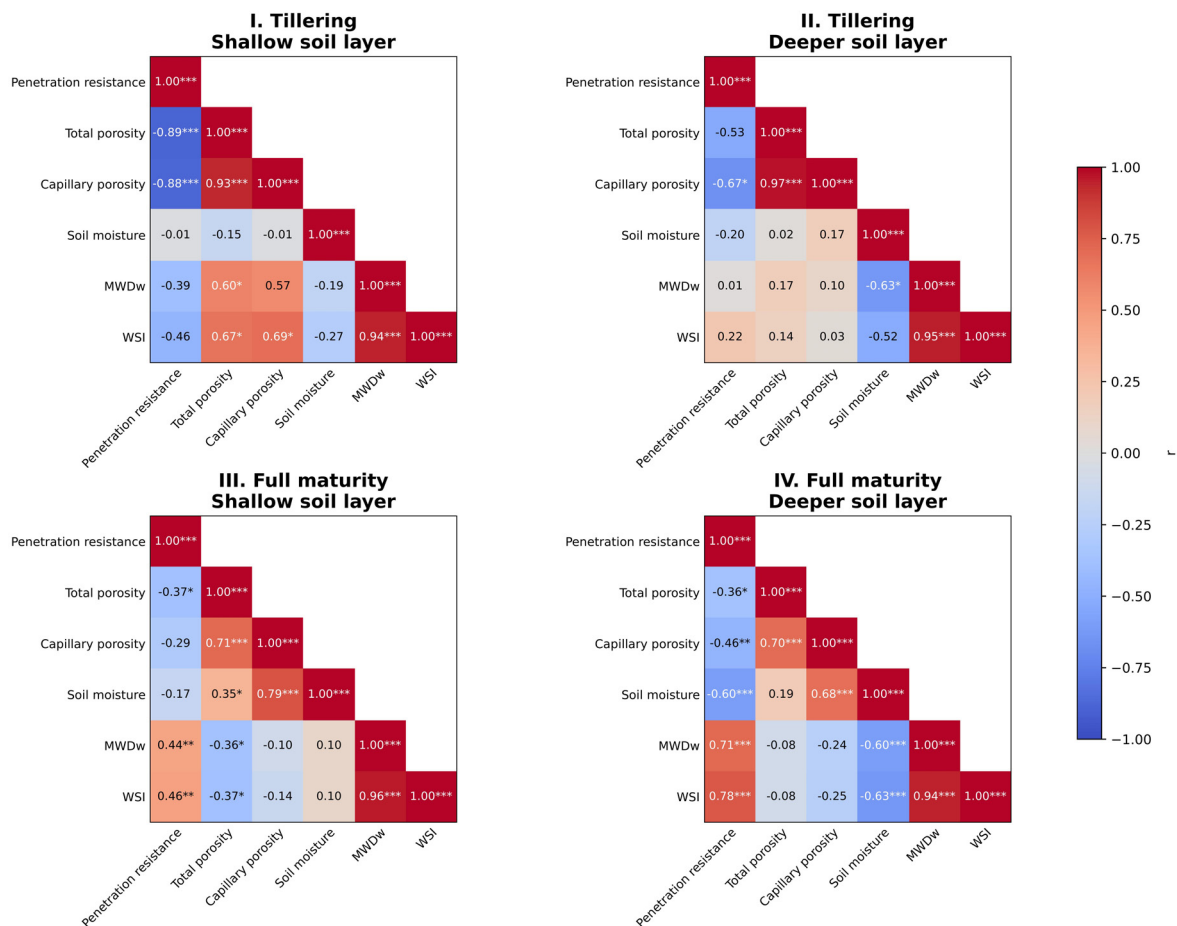


Fig. 1. Heatmaps of Pearson's correlation coefficients between selected soil physical properties at two sampling dates and in two soil layers. Colours indicate correlation coefficients (r), numbers in cells represent r values, and asterisks denote significance levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

an application rate of 40 kg N ha^{-1} , whereas higher nitrogen rates reduced this index by 11–15%. In the deeper layer, the effect of nitrogen fertilisation was not significant.

The interrelationships among the analysed soil physical properties were assessed based on Pearson's linear correlation coefficients, calculated separately for each measurement date and soil layer (Fig. 1). At the spring measurement date, in the shallower layer (panel I), soil penetration resistance exhibited a very strong negative correlation with both total and capillary porosity ($r = -0.89^{***}$ and $r = -0.88^{***}$, respectively), with a simultaneously very strong positive relationship between the two forms of porosity. Soil moisture remained essentially independent of the remaining analysed properties during this period. In the deeper layer (panel II), a very strong relationship between total and capillary porosity was maintained ($r = 0.97^{***}$), whereas the correlations between penetration resistance and porosity were weaker. Significant negative relationships between soil moisture and soil structural parameters emerged, including with MWDw ($r = -0.63^*$). At the sum-

mer measurement date, the direction of relationships was similar to that observed in spring, although their strength changed. In the shallower layer (panel III), a negative correlation between penetration resistance and total porosity was maintained ($r = -0.37^*$), and total porosity remained positively associated with capillary porosity ($r = 0.71^{***}$). The positive relationship between soil moisture and capillary porosity also became more pronounced ($r = 0.79^{***}$), whereas the relationships between total porosity and structural parameters were negative ($r = -0.36^*$ to -0.37^*). In the deeper layer (panel IV), a positive relationship between total and capillary porosity was maintained ($r = 0.70^{***}$). At the same time, soil moisture was negatively correlated with soil penetration resistance ($r = -0.60^{***}$) and aggregate stability parameters ($r = -0.60^{***}$ to -0.63^{***}).

In order to provide a synthetic representation of the co-variation among the analysed soil physical properties, principal component analysis (PCA) was applied, performed separately for each measurement date and soil layer (Table 8, Fig. 2). At the spring measurement date, in the

Table 8. Factor loadings of soil physical properties on the first two principal components (PC1 and PC2) obtained separately for each sampling term and soil layer

Variable	Tillering shallow soil layer		Tillering deeper soil layer		Full maturity shallow soil layer		Full maturity deeper soil layer	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Soil penetration resistance	0.829	0.424	0.804	0.107	-0.676	-0.150	-0.880	-0.074
Total soil porosity	-0.942	-0.176	-0.818	-0.468	0.787	-0.258	0.422	-0.794
Capillary porosity	-0.931	-0.276	-0.912	-0.368	0.700	-0.665	0.663	-0.680
Soil moisture	0.185	-0.781	-0.434	0.659	0.440	-0.781	0.830	-0.038
MWDw	-0.794	0.387	0.243	-0.939	-0.719	-0.632	-0.838	-0.444
WSI	-0.862	0.375	0.330	-0.882	-0.739	-0.618	-0.867	-0.440

Absolute loadings ≥ 0.70 are shown in bold.

shallower layer, PC1 reflected a gradient contrasting soils with higher penetration resistance against soils with greater porosity and higher aggregate stability, whereas PC2 was primarily associated with soil moisture. In the deeper layer, PC1 continued to describe the penetration resistance–porosity relationship, while PC2 was strongly associated with aggregate stability parameters (MWDw and WSI). At the summer measurement date, the arrangement of variables on the PCA axes underwent partial reorganisation. In the shallower layer, PC1 contrasted porosity against penetration resistance and soil structural parameters, whereas PC2 was strongly associated with soil moisture and capillary porosity. In the deeper layer, PC1 contrasted soils with higher moisture content against soils with greater penetration resistance and higher aggregate stability, while PC2 primarily reflected the variability in porosity.

The distribution of points on the PCA biplots (Fig. 2) confirmed the dominant role of tillage and cover crop management in differentiating soil physical properties. At the spring measurement date, no-tillage (NTcc) was clearly distinguished from conventional tillage treatments (CT and CTcc) along the PC1 axis, indicating its association with higher penetration resistance and distinct soil structural properties. In the deeper layer, treatment separation was additionally related to aggregation parameters. At the summer measurement date, treatment separation was maintained primarily along PC1, with reduced tillage (RTcc) and no-tillage (NTcc) positioned on the side of higher aggregate stability index values. The effect of nitrogen fertilisation was evident primarily in the shallower layer; however, it was of secondary importance and did not alter the fundamental pattern of treatment separation.

4. DISCUSSION

Tillage and cover crop management was the primary factor differentiating soil physical properties and exerted a stronger effect than nitrogen rates. The responses of the investigated parameters differed depending on the sampling date and soil depth, indicating the complex nature of the changes occurring in the soil. The applied treatments primarily differentiated the relationship between soil penetration resistance and porosity, which, in accordance with the literature, constitutes a fundamental indicator of soil physical condition, determining its hydraulic and mechanical properties (Hamza and Anderson, 2005; Rabot *et al.*, 2018). The results obtained confirm earlier reports indicating the key role of tillage intensity in shaping soil physical properties (Morris *et al.*, 2010; Nunes *et al.*, 2020).

No-tillage increased soil penetration resistance, particularly in the surface layer, accompanied by a decrease in total and capillary porosity. These results confirm previous reports indicating that the absence of mechanical loosening contributes to the compaction of the soil surface layer and deterioration of soil structural parameters (Martínez *et al.*, 2008; Lampurlanés and Cantero-Martínez, 2003). The strong negative correlation between penetration resistance and porosity indicates that this relationship was one of the key factors differentiating treatments in the present study. It should be noted that the literature points to the potentially transient nature of the increased penetration resistance frequently observed following the introduction of no-tillage systems. With the accumulation of soil organic matter, increased biological activity, and intensification of aggregation processes, a gradual stabilisation of the soil structure occurs (Six *et al.*, 2004), which over time may mitigate the initial increase in penetration resistance characteristic of no-tillage systems (Blanco-Canqui and Ruis, 2018). In the present study, only the early stage of this process

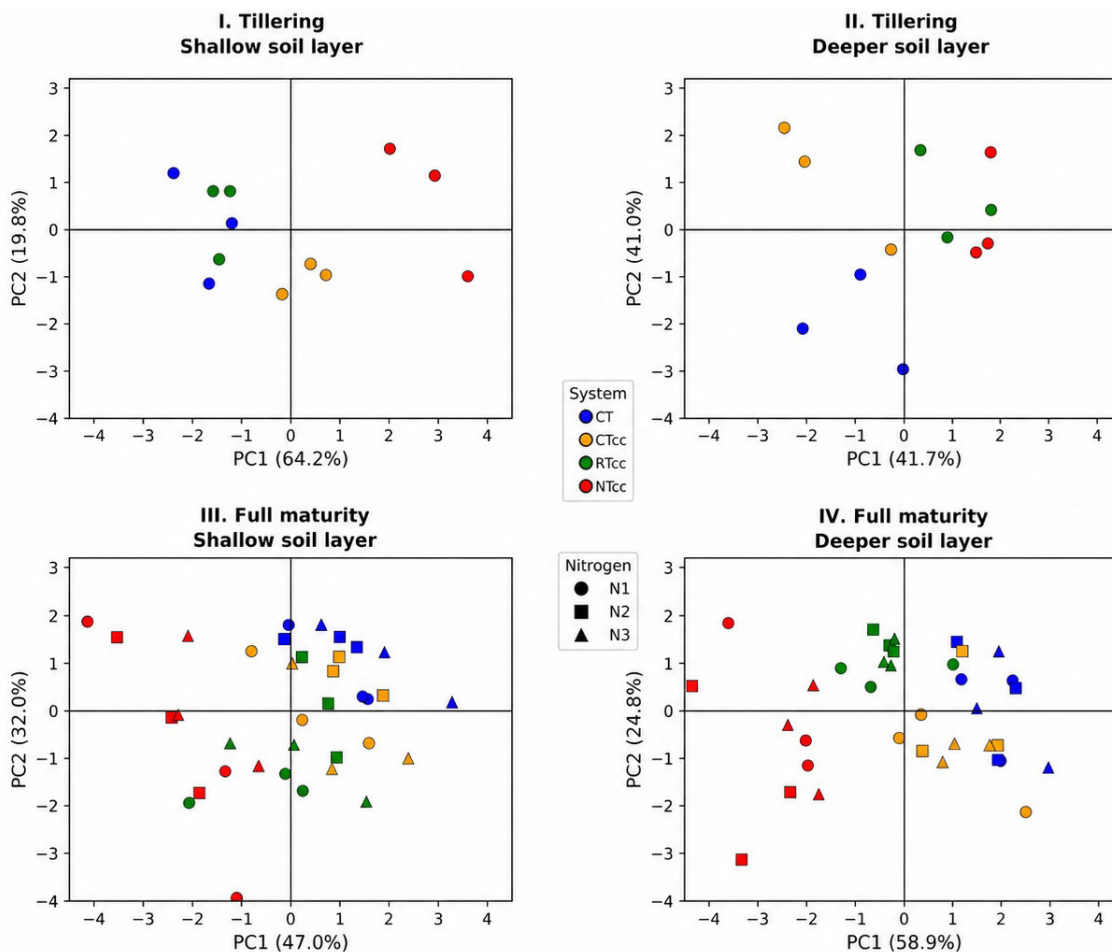


Fig. 2. Principal component analysis (PCA) of selected soil physical properties at two sampling dates and in two soil layers. Colours indicate tillage and cover crop management treatments, symbol shapes denote nitrogen rates, and axis labels show the percentage of variance explained by PC1 and PC2.

was recorded, suggesting that full stabilisation of physical properties requires a longer adaptation period under no-tillage conditions.

Soil structure is commonly described using various indices; however, no single parameter fully characterises aggregate properties and soil physical condition (Bieganowski *et al.*, 2010). Both the mean weight diameter of soil aggregates and their resistance to water disruption (MWDw and WSI) differed depending on the sampling date, confirming the dynamic nature of soil structural properties. Higher MWDw values under conventional tillage in spring may result from the transient effect of ploughing (Six *et al.*, 2004), as well as from the seasonal variability of soil physical conditions (Franzluebbers, 2002). However, at the summer measurement date, higher MWDw and aggregate water stability values were observed under reduced- and no-tillage systems than under conventional tillage. These results suggest that reducing tillage intensity promotes a gradual increase in aggregate stability. Similar relationships have also been reported in other studies, demonstrating

that minimising agronomic operations favourably affects the formation of a more durable soil structure over the longer term (Ferreira *et al.*, 2020; Lehmann *et al.*, 2017).

The stubble cover crop also played an important role in shaping soil aggregation parameters. In spring, under the treatment with an incorporated cover crop (CTcc), lower MWDw and aggregate water stability values were recorded than under the treatment without a cover crop (CT). This may result from the transient destabilisation of the soil structure caused by the rapid mineralisation of fresh biomass. However, at the summer measurement date, the reverse relationship was observed: treatments with a cover crop (CTcc, RTcc, and NTcc) were characterised by higher MWDw and WSI values than the treatment without a cover crop (CT). This phenomenon may be attributed to a later stage of biomass decomposition, when increased microbial activity and progressive humification of organic matter promote aggregate stabilisation and the formation of stable organo-mineral complexes (Oades, 1984). Recent studies also indicate that cover crops may improve soil

structure through plant- and microbial-mediated aggregate formation, including effects related to litter quality, root morphology and rhizosphere inputs (Hudek *et al.*, 2022; Gentsch *et al.*, 2024). This interpretation is consistent with findings indicating an increase in MWD and aggregate water stability values in systems with cover crops (Six *et al.*, 2004; Yan and Arthur, 2025). The results obtained confirm that cover crops are an important component of tillage and cover crop management, and that their effects on soil physical properties are dynamic and seasonally variable.

Soil moisture was less sensitive to tillage and cover crop management than aggregate stability, porosity and penetration resistance. The absence of significant differences at the spring measurement date and moderate differentiation at the summer measurement date are consistent with reports indicating the ambiguous nature of moisture responses to tillage intensity (Blanco-Canqui *et al.*, 2017). Differences recorded in the summer, particularly in the deeper layer, may be indirectly associated with differences in soil pore structure, which affects water retention, infiltration and hydraulic conductivity (Lipiec *et al.*, 2006; Rabot *et al.*, 2018). Reduced soil disturbance and cover crop residues may modify the continuity and size distribution of pores, thereby affecting both water storage and water movement within the soil profile. PCA results further confirmed that soil moisture constituted a distinct dimension of soil property variability.

The effects of nitrogen fertilisation on soil physical properties were limited, but not entirely negligible. No significant effects of nitrogen rates on penetration resistance, porosity, or moisture were found. Significant differences were recorded only for aggregation parameters (MWD_w and WSI), where higher nitrogen rates in the surface layer were associated with reduced aggregate stability. This response may be related to changes in the C:N balance and in the decomposition dynamics of plant residues and cover crop biomass. Higher nitrogen availability may accelerate the decomposition of plant residues and modify microbial activity, which may temporarily reduce the contribution of fresh organic binding agents to aggregate stabilisation (Franzluebbers, 2002; Khan *et al.*, 2007; Liu *et al.*, 2023). However, this effect was confined to aggregation parameters and did not alter the overall pattern of differentiation in soil physical properties among treatments. Similar observations have been reported in other studies, indicating that mineral fertilisation affects soil structure primarily indirectly, through changes in organic matter balance, residue decomposition and microbial activity (Angás *et al.*, 2006; Mulvaney *et al.*, 2009; Liu *et al.*, 2023).

The combined interpretation of ANOVA, correlation, and PCA results indicates that changes in soil physical properties were closely interrelated and predominantly determined by tillage and cover crop management, which is consistent with the concept of soil as an integrated structural-functional system (Rabot *et al.*, 2018). In spring, the

penetration resistance-porosity relationship played a key role, whereas in summer, properties associated with aggregate stability and soil moisture became more important. These results indicate that tillage intensity, as a component of tillage and cover crop management, remains the principal factor shaping the variability of soil structural properties, whereas the effect of nitrogen fertilisation is markedly weaker and exclusively indirect in nature.

The differentiation of soil structure among treatments may have significant implications for soil functioning, particularly regarding mechanical stability and water relations. Increased penetration resistance and reduced total porosity under no-tillage, particularly in the surface layer, may restrict initial root growth and impede gas exchange under conditions of extreme soil wetness, as these parameters are among the key factors governing root-soil interactions (Lipiec and Hatano, 2003; Bengough *et al.*, 2011; Rabot *et al.*, 2018). Meanwhile, the higher aggregate stability observed later in the growing season indicates a gradual stabilisation of soil structure, which may increase resistance to surface sealing and erosion (Le Bissonnais, 1996; Bronick and Lal, 2005) and may also favour improved water flow conditions in the soil through the development of a conducting pore system (Lipiec *et al.*, 2006). The seasonal transition from the dominant role of penetration resistance in spring to the greater importance of aggregate stability in summer indicates dynamic changes in the soil pore system. These changes may result from post-tillage soil settling, decomposition of cover crop residues, root growth, microbial activity and seasonal wetting-drying cycles. Together, these processes can modify pore continuity and aggregate stability. Consequently, they may affect water retention and soil resilience to mechanical loading and seasonal variability in hydrological conditions (Jarvis, 2007; Lal, 2015; Gentsch *et al.*, 2024).

The results should be interpreted in relation to the specific soil and climatic conditions of the study site. The three-year duration allowed seasonal and short-term treatment effects to be assessed, but may not fully reflect longer-term processes associated with soil structure stabilisation under reduced- and no-tillage conditions. Moreover, biological indicators, such as microbial activity, soil organic matter fractions or root biomass, were not directly measured; therefore, their role in aggregate stabilisation was inferred from soil physical responses and literature data. Consequently, the generalisation of the results to other soils and climatic regions should be made with caution. Future studies should include direct biological measurements to better explain the mechanisms linking cover crop biomass decomposition, microbial activity and soil structural stability.

5. CONCLUSIONS

1. Tillage and cover crop management was the dominant factor shaping soil physical properties, significantly differentiating penetration resistance, porosity, and aggregate stability in both analysed layers and at both measurement dates.

2. The absence of ploughing led to increased penetration resistance and reduced porosity in the early growing season, whereas reduced and no-tillage treatments promoted an increase in soil aggregate stability during the summer measurement period.

3. The effect of the cover crop was seasonal in nature: a transient reduction in aggregation parameters was observed in the early growing season, whereas a significant improvement in aggregate stability occurred towards the end of the season.

4. The penetration resistance-porosity relationship constituted the primary mechanism differentiating treatments, as confirmed by correlation and PCA analyses.

5. The effect of nitrogen fertilisation on soil physical properties was limited. A significant effect was recorded primarily with respect to aggregation parameters in the shallower layer, where higher nitrogen rates reduced soil structural stability.

6. Reduced tillage with a cover crop promoted soil structure stabilisation, with the beneficial effect becoming apparent only in the later part of the growing season.

Research concept and design: R.W.; collection and/or assembly of data: M.G., P.K., and A.L.-S.; data analysis and interpretation: R.W., M.G., D.G., and S.A.; writing the article: R.W., M.G., P.K., and A.L.-S.; critical revision of the article: R.W., P.K., D.G., and S.A.; final approval of the article: all authors. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare that they have no conflict of interest.

6. REFERENCES

- Angás, P., Lampurlán, J., Cantero-Martínez, C., 2006. Tillage and N fertilisation effects on N dynamics and barley yield under semiarid Mediterranean conditions. *Soil Till. Res.* 87(1), 59-71. <https://doi.org/10.1016/j.still.2005.02.036>
- Bai, T., Wang, P., Ye, C., Hu, S., 2021. Form of nitrogen input dominates N effects on root growth and soil aggregation: A meta-analysis. *Soil Biology Biochemistry* 157, 108251. <https://doi.org/10.1016/j.soilbio.2021.108251>
- Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Experimental Botany* 62(1), 59-68. <https://doi.org/10.1093/jxb/erq350>
- Bieganski, A., Ryzak, M., Witkowska-Walczak, B., 2010. Determination of soil aggregate disintegration dynamics using laser diffraction. *Clay Minerals* 45(1), 23-34. <https://doi.org/10.1180/claymin.2010.045.1.23>
- Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods*. ASA-SSSA, Madison, WI, 363-375.
- Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. *Geoderma* 326, 164-200. <https://doi.org/10.1016/j.geoderma.2018.03.011>
- Blanco-Canqui, H., Wienhold, B.J., Jin, V.L., Schmer, M.R., Kibet, L.C., 2017. Long-term tillage impact on soil hydraulic properties. *Soil Till. Res.* 170, 38-42. <https://doi.org/10.1016/j.still.2017.03.001>
- Bronick, C.J., Lal, R., 2005. Soil structure and management: A review. *Geoderma* 124(1-2), 3-22. <https://doi.org/10.1016/j.geoderma.2004.03.005>
- Çerçioğlu, M., Anderson, S.H., Udawatta, R.P., Alagele, S., 2019. Effect of cover crop management on soil hydraulic properties. *Geoderma* 343, 247-253. <https://doi.org/10.1016/j.geoderma.2019.02.027>
- Dai, W., Feng, G., Adeli, A., Brooks, J.P., 2025. Effects of cover crops on soil aggregate-associated organic carbon and nitrogen characteristics in a cotton-corn rotation system. *Soil Sci. Soc. Am. J.* 89(5), e70137. <https://doi.org/10.1002/saj2.70137>
- dos Reis Ferreira, C., da Silva Neto, E.C., Pereira, M.G., do Nascimento Guedes, J., Rosset, J.S., dos Anjos, L.H.C., 2020. Dynamics of soil aggregation and organic carbon fractions over 23 years of no-till management. *Soil Till. Res.* 198, 104533. <https://doi.org/10.1016/j.still.2019.104533>
- Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. *Soil Till. Res.* 66(2), 95-106. [https://doi.org/10.1016/S0167-1987\(02\)00018-1](https://doi.org/10.1016/S0167-1987(02)00018-1)
- Gabriel, J.L., Quemada, M., Martín-Lammerding, D., Vanclouster, M., 2019. Assessing the cover crop effect on soil hydraulic properties by inverse modelling in a 10-year field trial. *Agric. Water Manag.* 222, 166-177. <https://doi.org/10.1016/j.agwat.2019.05.034>
- Gajewski, P., Majchrzak, L., Bocianowski, J., Kaczmarek, Z., 2025. Effects of cover crops and tillage methods on selected physical and water-retention properties of Luvisol. *Int. Agrophys.* 39, 73-86. <https://doi.org/10.31545/intagr/195906>
- Gentsch, N., Riechers, F.L., Boy, J., Schwenker, D., Feuerstein, U., Heuermann, D., *et al.*, 2024. Cover crops improve soil structure and change organic carbon distribution in macro-aggregate fractions. *Soil* 10, 139-150. <https://doi.org/10.5194/soil-10-139-2024>
- Hamza, A., Karčauskienė, D., Mockevičienė, I., Repšienė, R., Tahir, M.A., Manzoor, M.Z., *et al.*, 2025. Soil aggregate dynamics and stability: Natural and anthropogenic drivers. *Agriculture* 15(23), 2500. <https://doi.org/10.3390/agriculture15232500>
- Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes, and possible solutions. *Soil Till. Res.* 82(2), 121-145. <https://doi.org/10.1016/j.still.2004.08.009>
- Herrick, J.E., Jones, T.L., 2002. A dynamic cone penetrometer for measuring soil penetration resistance. *Soil Sci. Soc. Am. J.* 66, 1320-1324. <https://doi.org/10.2136/sssaj2002.1320>
- Hudek, C., Putinica, C., Otten, W., De Baets, S., 2022. Functional root trait-based classification of cover crops to improve soil physical properties. *Eur. J. Soil Sci.* 73, e13147. <https://doi.org/10.1111/ejss.13147>

- IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps, 4th ed. International Union of Soil Sciences, Vienna, Austria.
- Jarvis, N., 2007. A review of non-equilibrium water flow and solute transport in soil macropores. *Eur. J. Soil Sci.* 58(3), 523-546. <https://doi.org/10.1111/j.1365-2389.2007.00915.x>
- Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods*. ASA-SSSA, Madison, WI, 425-442.
- Khan, S.A., Mulvaney, R.L., Ellsworth, T.R., Boast, C.W., 2007. The residue question: Nitrogen fertiliser and the loss of soil organic matter. *J. Environ. Quality* 36(6), 1821-1832. <https://doi.org/10.2134/jeq2007.0099>
- Lal, R., 2015. Restoring soil quality to mitigate soil degradation. *Sustainability* 7, 5875-5895. <https://doi.org/10.3390/su7055875>
- Lampurlanés, J., Cantero-Martínez, C., 2003. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. *Agronomy J.* 95(3), 526-536. <https://doi.org/10.2134/agronj2003.5260>
- Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* 47(4), 425-437. <https://doi.org/10.1111/j.1365-2389.1996.tb01843.x>
- Lehmann, A., Zheng, W., Rillig, M.C., 2017. Soil biota contributions to soil aggregation. *Nature Ecology Evolution* 1, 1828-1835. <https://doi.org/10.1038/s41559-017-0344-y>
- Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop growth. *Geoderma* 116(1-2), 107-136. [https://doi.org/10.1016/S0016-7061\(03\)00097-1](https://doi.org/10.1016/S0016-7061(03)00097-1)
- Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. *Soil Till. Res.* 89, 210-220. <https://doi.org/10.1016/j.still.2005.07.012>
- Liu, Y., Zhang, W., Chen, X., Zhou, H., Wang, J., 2023. Influence of long-term fertilisation on soil aggregate stability and aggregate-associated organic carbon. *Frontiers in Plant Science* 14, 1126150. <https://doi.org/10.3389/fpls.2023.1126150>
- Martínez, E., Fuentes, J.P., Silva, P., Valle, S., Acevedo, E., 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. *Soil Till. Res.* 99(2), 232-244. <https://doi.org/10.1016/j.still.2008.02.001>
- Mocek, A. (Ed.), 2020. *Gleboznawstwo* (in Polish). 1st ed. Publishing House of the Poznań University of Life Sciences, Poznań.
- Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment – A review. *Soil Till. Res.* 108(1-2), 1-15. <https://doi.org/10.1016/j.still.2010.03.004>
- Mulvaney, R.L., Khan, S.A., Ellsworth, T.R., 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. *J. Environ. Quality* 38(6), 2295-2314. <https://doi.org/10.2134/jeq2008.0527>
- Nouri, A., Lee, J., Yin, X., Tyler, D.D., Saxton, A.M., 2019. Thirty-four years of no-tillage and cover crops improve soil quality and increase cotton yield in Alfisols, Southeastern USA. *Geoderma* 337, 998-1008. <https://doi.org/10.1016/j.geoderma.2018.10.016>
- Nunes, M.R., Karlen, D.L., Moorman, T.B., Cambardella, C.A., Laird, D.A., 2020. Tillage intensity effects on soil structure indicators: A US meta-analysis. *Sustainability* 12(5), 2071. <https://doi.org/10.3390/su12052071>
- Oades, J.M., 1984. Soil organic matter and structural stability: Mechanisms and implications for management. *Plant Soil* 76(1-3), 319-337. <https://doi.org/10.1007/BF02205590>
- Pearsons, K.A., Rui, Y., Kladvko, E.J., 2025. Decade-long cereal rye cover cropping improved soil carbon and physical properties of a poorly structured silt loam. *Soil Sci. Soc. Am. J.* 89(6), e70165. <https://doi.org/10.1002/saj2.70165>
- Piazza, G., Pellegrino, E., Moscatelli, M.C., Ercoli, L., 2020. Long-term conservation tillage and nitrogen fertilisation effects on soil aggregate distribution, nutrient stocks and enzymatic activities in bulk soil and occluded microaggregates. *Soil Till. Res.* 196, 104482. <https://doi.org/10.1016/j.still.2019.104482>
- Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: A review. *Geoderma* 314, 122-137. <https://doi.org/10.1016/j.geoderma.2017.11.009>
- Rocco, S., Munkholm, L.J., Jensen, J.L., 2024. Long-term soil quality and C stock effects of tillage and cover cropping in a conservation agriculture system. *Soil Till. Res.* 241, 106129. <https://doi.org/10.1016/j.still.2024.106129>
- Schmidt, E.S., Villamil, M.B., Amiotti, N.M., 2018. Soil quality under conservation practices on farm operations of the southern semiarid pampas region of Argentina. *Soil Till. Res.* 176, 85-94. <https://doi.org/10.1016/j.still.2017.11.001>
- Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Till. Res.* 79(1), 7-31. <https://doi.org/10.1016/j.still.2004.03.008>
- Spasić, M., Vacek, O., Vejvodová, K., Tejnecký, V., Polák, F., Borůvka, L., *et al.*, 2023. Determination of physical properties of undisturbed soil samples according to V. Novák. *MethodsX* 10, 102133. <https://doi.org/10.1016/j.mex.2023.102133>
- Wang, Y., Zou, L., Lou, C., Geng, X., Zhang, S., Chen, X., *et al.*, 2024. No-tillage with straw retention influenced maize root growth morphology by changing soil physical properties and aggregate structure in Northeast China: A ten-year field experiment. *Geoderma Regional* 38, e00840. <https://doi.org/10.1016/j.geodrs.2024.e00840>
- Yan, F., Arthur, E., 2025. Cover crops alter soil physicochemical properties: A global meta-analysis. *Geoderma* 460, 117436. <https://doi.org/10.1016/j.geoderma.2025.117436>
- Zhang, B., Jia, Y., Fan, H., Guo, C., Fu, J., Li, S., 2024. Soil compaction due to agricultural machinery impact: A systematic review. *Land Degradation and Development* 35(10), 3256-3273. <https://doi.org/10.1002/ldr.5144>