JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.158716
2026, No. 69 (IV–VI): 188–196

Canopy development and yield performance of spring wheat under long-term tillage systems: implications for sustainable crop management

Beata Michalska-Klimczak*[1)], Sonia Kamińska-Stępień[1)], Vladimir Pacuta[2)], Marek Rašovský[2)], Zdzisław Wyszyński[1)]

[1)] Warsaw University of Life Sciences-SGGW, Institute of Agriculture, Department of Agronomy, Nowoursynowska St, 159, 02-776 Warsaw, Poland

[2)] Slovak University of Agriculture in Nitra, Faculty of Agrobiology and Food Resources, Department of Crop Production and Grassland Ecosystems, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia

* Corresponding author

RECEIVED 15.07.2025 ACCEPTED 06.02.2026 AVAILABLE ONLINE 16.06.2026

Abstract: Understanding how tillage practices influence canopy development in spring wheat (*Triticum aestivum* L.) is essential for improving productivity in sustainable farming systems, particularly in temperate regions with variable spring moisture. This study assessed the effects of conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) on spring wheat canopy structure and architecture and examined their relationships with yield formation. A three-season field experiment was conducted on Luvisol soils in central Poland within a four-course crop rotation. Canopy traits, including plant and shoot density, the share of productive shoots, shoot-type distribution, shoot length, spike morphology, and grain parameters, were measured at key growth stages. CT improved stand establishment, tillering capacity, and spike productivity, producing the highest grain yield in all seasons. By contrast, NT reduced the proportion of multi-shoot and fertile plants, shortened spikes, and reduced grain weight, resulting in a yield decline of more than 30% relative to CT. Strong correlations were observed between canopy structure and grain yield and between architectural traits and spike performance. These findings indicate that tillage systems should be evaluated not only in terms of soil-related benefits but also according to their ability to support canopy functionality and yield resilience under increasingly variable climatic conditions.

Keywords: canopy architecture, canopy structure, grain yield, spring wheat, tillage system

INTRODUCTION

Balancing agricultural productivity with environmental sustainability is one of the most pressing challenges in farming systems. Soil tillage practices play a central role in this context, especially in temperate regions, because they influence soil structure, water retention, organic matter dynamics, and crop establishment. Conventional tillage (CT), typically involving mouldboard ploughing to a depth of 20–25 cm, has long been favoured for its ability to suppress weeds, promote rapid soil warming, and create a fine seedbed that enhances germination and uniform crop emergence (Kassam *et al.*, 2009; Barut and Çelik, 2010). However, concerns about soil erosion, compaction, carbon loss, and greenhouse gas emissions have encouraged a shift towards reduced tillage (RT) and no-tillage (NT) systems within conservation agriculture (Hobbs, Sayre and Gupta, 2008; Pittelkow *et al.*, 2015; Chataut *et al.*, 2023). Reduced tillage and no-tillage practices can improve soil physical properties, enhance biological activity, and increase carbon sequestration over the long term (Tebrügge and Düring, 1999; Machado, Rhinhart and Petrie, 2006). Nonetheless, their agronomic performance, especially for spring-sown crops, remains inconsistent and context-specific. This is particularly evident in Central and Eastern Europe, where light-textured soils, irregular spring precipitation, and shallow rooting zones amplify the risks associated with limited early soil loosening (Soane *et al.*, 2012; Steponavičienė *et al.*, 2024). In spring wheat (*Triticum aestivum* L.), a crop with a short vegetative phase and limited compensatory capacity, canopy development during early growth is critical for final yield formation (Dhanda and Sethi, 2002; Kiss *et al.*, 2018).

Although many previous studies have addressed the effects of tillage on soil fertility, weed control, and crop yield, far fewer have examined how tillage influences aboveground plant architecture, which is a key determinant of light interception, assimilate partitioning, and spike productivity (Tørresen *et al.*, 2003; Farooq *et al.*, 2011; Carr, Gramig and Liebig, 2013; Karlen *et al.*, 2013; Shahzad *et al.*, 2016; Cárcer de *et al.*, 2019). Canopy structure (e.g., plant density, tiller number, and shoot spatial distribution) and canopy architecture (e.g., shoot length, spike morphology, and grain number per spike) are essential phenotypic traits linking tillage-induced soil conditions with reproductive success and yield formation (Evers *et al.*, 2007; Gaju *et al.*, 2009; Křen *et al.*, 2013; Paulus *et al.*, 2014). Understanding these traits is particularly important for spring wheat cultivation, where early stand establishment and tiller survival determine the number of productive shoots and spike size (Sułek, Wyzińska and Cacak-Pietrzak, 2019; Mwendwa *et al.*, 2020).

Recent research shows that tillage systems can strongly modify microenvironmental conditions, including temperature, soil moisture, and mechanical impedance, which in turn influence root vigour, tiller initiation, and shoot morphology (Zheng *et al.*, 2014; Iqbal *et al.*, 2022; Huang *et al.*, 2024). In CT systems, more favourable seedbed conditions often translate into higher plant density and a greater proportion of productive tillers. By contrast, RT and NT systems may delay emergence, reduce tillering intensity, and lower spike fertility. This response is especially relevant under stressful conditions, such as early-season drought or waterlogging (Lonbani and Arzani, 2011; Rajala *et al.*, 2011; Jalli *et al.*, 2021). These effects can accumulate across canopy levels and ultimately affect yield components such as spike number per square metre, grain number per spike, and thousand grain weight (López-Bellido *et al.*, 2023; Zhou *et al.*, 2021).

Despite their agronomic relevance, canopy-level traits often remain underutilised in evaluations of tillage systems. Given increasing climate variability and the demand for more resilient cropping systems, a clearer understanding of how tillage shapes canopy design and yield components is essential for designing and implementing sustainable intensification strategies.

This study evaluated the effects of three contrasting tillage systems–conventional tillage, reduced tillage, and no-tillage–on canopy structure and architecture in spring wheat and assessed how these traits influence yield formation. The specific objectives were to: (i) quantify the effects of tillage on plant density, shoot number, and spike morphology; (ii) determine the relationships between structural and architectural traits and key yield components; and (iii) identify tillage strategies that optimise spring wheat canopy performance and productivity under temperate climatic conditions.

We hypothesised that long-term tillage systems significantly modify spring wheat canopy structure and architecture and that these changes determine yield components and overall productivity under temperate climatic conditions.

MATERIALS AND METHODS

EXPERIMENTAL SITE

The field experiment with spring wheat was conducted at the Experimental Field in Miedniewice (51°58'N i 20°11'E), located in central Poland. The site belongs to a long-term crop rotation trial established at the Institute of Agriculture, Warsaw University of Life Sciences (WULS-SGGW), to evaluate the agronomic and ecological effects of different tillage systems on crop productivity. The present study used data from three growing seasons (2012, 2016, and 2020), which form part of a broader multiyear dataset that continues to be expanded.

The soil at the experimental site was classified as a Luvisol according to the WRB classification (IUSS Working Group WRB, 2022). The experiment was conducted on a leached rainwater-gley soil (pseudogley), classified as soil quality classes IIIb and IVa and belonging to the very good rye soil complex. The soil was formed from loamy sands (light and strong) overlying light loam. It was slightly acidic (pH 6.0), with medium phosphorus content (37 mg·kg^{-1}) and high potassium (170 mg·kg^{-1}) and magnesium (144 mg·kg^{-1}) concentrations.

WEATHER CONDITIONS

Weather conditions during the three experimental years showed substantial interannual variability, strongly influencing the water and thermal environment for spring wheat development (Tab. 1). The first season (2012) was the driest, with total precipitation of only 201.1 mm, far below the optimal requirement of 283 mm. Particularly severe water stress occurred in May (rainfall = 21.4 mm; hydrothermal coefficient (*Hk*) = 0.44), a critical phase for shoot elongation and spikelet formation. Although

Table 1. Weather conditions during the three years of the experiment

Year	Months				Sum for Apr–Jul
	Apr	May	Jun	Jul	
Rainfall (mm)					
2012	52.8	21.4	57.7	69.2	201.1
2016	49.6	127.5	149.4	17.7	344.2
2020	49.8	92.6	60.2	82.8	285.4
Rainfall requirements[1)]	45.0	66.0	83.0	89.0	283.0
Monthly average temperature (°C)					
2012	9.4	15.6	17.4	20.6	–
2016	7.6	14.6	18.1	19.9	–
2020	10.3	14.1	16.4	20.9	–
Hydrothermal coefficient[2)] (*Hk*) (–)					
2012	1.87	0.44	1.11	1.08	–
2016	2.18	2.82	2.75	0.29	–
2020	1.61	2.12	1.22	1.28	–

[1)] Dzieżyc, Nowak and Panek (1987). [2)] Selyaninov (1928).
Source: own elaboration.

temperatures were favourable, including a warm July (20.6°C), the irregular and limited water supply probably constrained yield formation. The second season (2016) was the wettest (344.2 mm), with excessive rainfall in May and June (127.5 and 149.4 mm, respectively), resulting in high *Hk* values (>2.7). However, a sharp decline in rainfall in July (17.7 mm; *Hk* = 0.29) introduced moisture stress during grain filling, potentially affecting final yield and grain quality. The third season (2020) was the most agroclimatically favourable, with near-optimal precipitation (285.4 mm) and a balanced *Hk* distribution (1.22–2.12). Moderate rainfall and stable temperature increases, including a warm April (10.3°C) and July (20.9°C), created conducive conditions for both vegetative and generative stages of wheat development. Overall, the 2020 season provided the most suitable weather pattern for high spring wheat productivity.

EXPERIMENTAL DESIGN

The field experiment with spring wheat was conducted as part of a long-term crop rotation system. The four-course rotation included sugar beet, spring wheat, yellow lupin, and winter wheat, representing a crop sequence typical of sustainable farming systems. Spring wheat was grown in the same field every four years (2012, 2016, and 2020) within this cycle, reflecting common rotational practice and enabling consistent monitoring of tillage effects on canopy development and productivity across multiple cycles. Thus, the three seasons analysed in this study correspond to three consecutive rotation cycles rather than successive calendar years, allowing long-term evaluation of tillage effects under contrasting hydrothermal conditions.

The spring wheat cultivar 'Tybalt' (*Triticum aestivum* L.) was used in all experimental years to maintain consistency within the long-term rotation and ensure comparability of tillage effects across rotation cycles.

The main experimental factor was the tillage system, implemented in three variants representing different intensities of soil disturbance. In the conventional tillage (CT) system, soil management began with post-harvest cultivation using either a disc harrow or a rigid-tine cultivator (commonly referred to as a grubber), depending on prevailing soil moisture conditions. This was followed by winter ploughing to a depth of 25 cm with a mouldboard plough. In the reduced tillage (RT) system, the same post-harvest cultivation was used, but ploughing was replaced by non-inversion tillage with a grubber to a depth of 20 cm. The no-tillage (NT) treatment was based on direct sowing into undisturbed soil without mechanical presowing cultivation. Weed control in NT was performed with herbicides applied either immediately after harvest of the previous crop or just before sowing. Spring wheat was sown in early April in each season (8 April in 2012 and 2016, and 7 April in 2020). The seeding rate was uniform across treatments at 220 kg·ha^{-1}. In CT and RT, sowing was performed using a cereal row drill equipped with disc coulters and 13 cm row spacing. In NT, sowing was performed using a Vredo direct seeding drill with 10 cm row spacing to improve seed-to-soil contact under undisturbed surface conditions. Before sowing, all plots received a uniform dose of compound mineral fertiliser, Polifoska 8 (NPK 8-24-24), at 350 kg·ha^{-1}. Ammonium nitrate (34% N) was also applied at 100 kg·ha^{-1} as a starter nitrogen dose. At stem elongation (BBCH 30-31), a second nitrogen application was made using the same fertiliser at 250 kg·ha^{-1} to support vegetative and generative development. Crop protection treatments, including herbicide, fungicide, and insecticide applications, were applied as needed and in accordance with recommendations of the Institute of Plant Protection – National Research Institute (Pol.: Instytut Ochrony Roślin – Państwowy Instytut Badawczy) in Poznań (Korbas, Horoszkiewicz-Janka and Mrówczyński (eds.), 2017). The experiment was arranged in a randomised complete block design with three replications per tillage treatment, giving nine plots in total. Each plot had an area of 150 m^2 (10 × 15 m), allowing spatially representative sampling and field-scale yield assessment.

PLANT SAMPLING AND MEASUREMENTS

To characterise canopy development and productivity in spring wheat, the following parameters were measured:
- canopy structure traits, including the number of emerged plants (pcs.·m^{-2}), number of shoots after tillering (pcs.·m^{-2}), number of productive and non-productive shoots at harvest (pcs.·m^{-2}), and the percentage share of plant groups with a specific number of productive shoots in the canopy at harvest;
- canopy architecture traits, including shoot and spike length (cm), number of grains per spike (pcs.), and grain weight per spike (g), expressed as average values for plants with 1, 2, 3, and 4 or more shoots within each tillage system;
- grain yield (g·m^{-2}) and its components: number of spikes (pcs.·m^{-2}), number of grains per spike (pcs.), and thousand grain weight (TGW, g).

Canopy structure and architecture traits were evaluated in three fixed sampling areas (D, E, and F) located in the same positions within each plot (Fig. 1). Each area included three 1.0 m rows of plants. Canopy structure traits were assessed in nine rows per plot, corresponding to 1.17 m^2 (9 rows, 1 m long, 13 cm spacing) for conventional and reduced tillage and 0.90 m^2 (9 rows, 1 m long, 10 cm spacing) for no-tillage. The number of emerged plants was recorded at the three-leaf stage (BBCH 13), the number of shoots after tillering at shoot elongation (BBCH 33–34), and the number of productive and non-productive shoots immediately before harvest (BBCH 92).

Canopy architecture traits were assessed on plants excavated at harvest from the third rows of each designated area (D, E, and F) (Fig. 1). Each plot sample included plants from three rows, covering 0.39 m^2 in conventional and reduced tillage or 0.30 m^2 in no-tillage. Within each sample, plants were divided into groups with 1, 2, 3, or 4 or more shoots, and the number of plants in each group was recorded. Individual plants were then separated into shoots, and the lengths of main and lateral shoots, as well as spike lengths, were measured. Spikes from each shoot were placed in envelopes labelled with the plant number, shoot length, and spike length; the number and weight of grains per spike were then determined. Canopy architecture data are presented as mean values for single-shoot plants and as average shoot values for the respective multi-shoot plant groups (2, 3, and 4 or more shoots).

Grain yield and its components were assessed at the end of the growing season in three corresponding areas per plot (A, B, and C) (Fig. 1). In conventional and reduced tillage, spikes were harvested from 1.04 m^2 (8 rows, 1 m long, 13 cm spacing), whereas in no-tillage they were harvested from 1.00 m^2 (10 rows, 1 m long, 10 cm spacing). After the number of spikes in each sample had been counted, the spikes were threshed and the grain

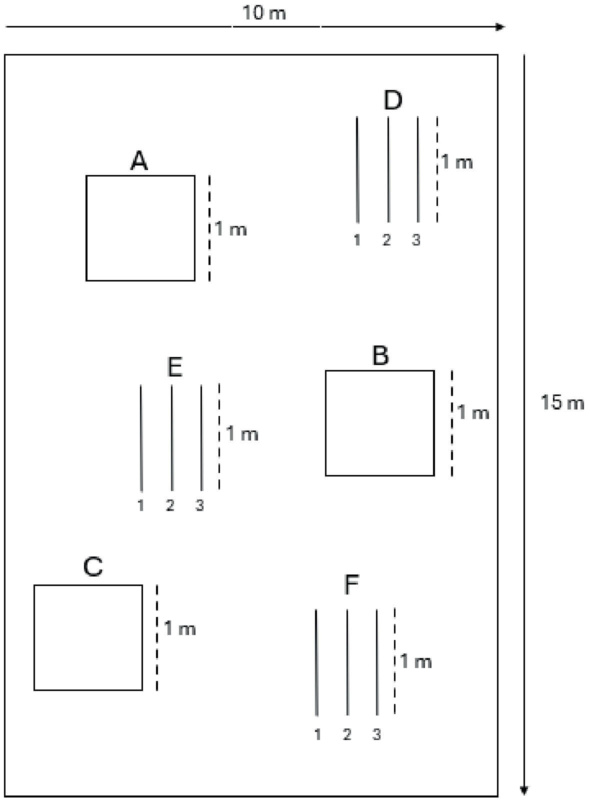

Fig. 1. Schematic layout of an experimental plot (10 × 15 m) divided into six fixed sampling zones (A–F). Zones A, B, and C were designated for grain yield and yield component assessment, while zones D, E, and F were used for canopy structure and architecture measurements; source: own elaboration.

was weighed. Thousand grain weight (TGW) was determined, and the average number of grains per spike was calculated from the number of spikes, TGW, and total grain weight. Grain yield and yield components for conventional and reduced tillage were recalculated per 1 m^2. Yield data for each plot represent mean values from the three sampling areas (A, B, and C).

STATISTICAL ANALYSIS

The experimental data were analysed using TIBCO Statistica™ 13.3.0 software (TIBCO Software Inc., 2017). One-way analysis of variance (ANOVA) was performed separately for each year, with tillage system as the main factor. Two-way ANOVA was also conducted for combined data from the three-year period, with tillage system and year as factors. Differences between means were evaluated using Tukey's HSD test at a significance level of $\alpha = 0.05$. To determine relationships between canopy structure traits and grain yield, as well as between canopy architecture traits and grain weight per spike, Pearson correlation coefficients were calculated.

RESULTS

CANOPY STRUCTURE TRAITS

The tillage system significantly affected spring wheat canopy structure across all three years of the study (Tab. 2). The number of emerged plants per square metre was consistently highest under conventional tillage (CT), with a three-year average of 493.0 pcs.·m^{-2}. This was 8.5% higher than under reduced tillage (RT) and 33.6% higher than under no-tillage (NT). Year-to-year comparisons showed that CT produced higher plant density than RT by 6.6% in 2012, 12.7% in 2016, and 6.2% in 2020. Compared with NT, the differences were greater: 25.0, 63.3, and 18.0%, respectively. Reduced tillage also resulted in higher plant emergence than no-tillage, with a mean increase of 23.1% across the study period. This trend was evident in each year, especially in 2016, when emergence under RT exceeded that under NT by 73.9%. In terms of shoot development, CT again produced the most favourable outcomes. The average number of shoots after tillering was 635.9 pcs.·m^{-2} under CT, compared with 596.7 under RT and 509.2 under NT, corresponding to increases of 6.6 and 24.9%, respectively. The shoot density advantage of CT over RT ranged from 2.1 to 13.2%, and that over NT ranged from 14.9 to 32.0%, depending on the year. Conventional tillage also promoted greater tillering diversity within the canopy. The share

Table 2. Structural traits of spring wheat canopy under different tillage systems

Tillage system	Years			
	2012	2016	2020	mean
Number of plants after emergence (pcs.·m^{-2})				
Conventional (CT)	550.2	512.3	416.5	493.0
Reduced (RT)	516.0	545.7	392.3	454.3
No-tillage (NT)	440.3	313.8	353.0	369.0
$LSD_{0.05}$	21.8*	34.3*	5.7*	10.6*
Mean	502.2	426.9	387.3	
Number of shoots after tillering (pcs.·m^{-2})				
Conventional (CT)	628.8	618.5	660.3	635.9
Reduced (RT)	616.0	546.5	627.7	596.7
No-tillage (NT)	484.4	468.7	574.5	509.2
$LSD_{0.05}$	39.7*	60.0*	77.0*	25.4*
Mean	576.4	544.6	620.8	
Number of productive shoots (pcs.·m^{-2})				
Conventional (CT)	569.7	535.0	525.4	543.4
Reduced (RT)	523.7	465.0	494.5	494.4
No-tillage (NT)	413.3	421.4	438.1	424.3
$LSD_{0.05}$	17.7*	31.5*	10.5*	11.4*
Mean	502.2	473.8	486.0	
Number of non-productive shoots (pcs.·m^{-2})				
Conventional (CT)	17.6	18.5	20.0	18.7
Reduced (RT)	21.4	19.7	19.9	20.3
No-tillage (NT)	24.7	21.9	21.1	22.5
$LSD_{0.05}$	17.8	18.7	3.1	6.7
Mean	21.2	20.0	20.3	

Explanations: *LSD* = least significant difference, * = significant at $\alpha = 0.05$.
Source: own study.

of plants with three or more shoots was highest in this system, averaging 6.7% for three-shoot plants and 1.8% for plants with four or more shoots, suggesting more favourable conditions for lateral shoot development (Tab. 3).

Table 3. Share of spring wheat plants (%) with a specific number of productive shoots in a canopy depending on the tillage system

Tillage system	Plants			
	1-shoot	2-shoots	3-shoots	≥4 shoots
Conventional (CT)	66.5	25.0	6.7	1.8
Reduced (RT)	70.2	23.6	5.3	0.9
No-tillage (NT)	68.5	24.7	6.1	0.8

Source: own study.

CANOPY ARCHITECTURE TRAITS

Spring wheat architecture was also affected by the tillage system (Tab. 4). Across all shoot categories, shoot length was consistently greatest under CT. For example, shoots of single-shoot plants were 14.3% longer under CT than under no-tillage and 7.5% longer than under RT. Similar trends were observed for plants with 2, 3, and 4 or more shoots, with differences ranging from 1.2 to 23.3% in favour of CT.

Spike length followed a similar pattern. On average, spikes of single-shoot plants were 6.8% longer under CT than under RT, and spikes of plants with four or more shoots were 11.4% longer. No-tillage produced noticeably shorter spikes, particularly in plants with stronger tillering. The number of grains per spike was highest under CT across all shoot categories. In single-shoot plants, it exceeded values under RT and NT by 13.3 and 16.6%, respectively. Among plants with four or more shoots, the increase relative to NT reached 36.5%. Grain weight per spike showed the same tendency. Compared with RT, CT increased grain weight by 20.0% in single-shoot plants and by 37.5% in plants with four or more shoots. Compared with NT, the relative advantage ranged from 20.0 to 57.1%, depending on tillering category.

Table 4. Architecture traits of spring wheat canopy under different tillage systems

Tillage system	Plants			
	1-shoot	2-shoots	3-shoots	≥4 shoots
Shoot length (cm)				
Conventional (CT)	64.6	61.3	60.4	63.8
Reduced (RT)	60.1	59.6	59.7	56.6
No-tillage (NT)	56.5	56.0	55.1	51.8
$LSD_{0.05}$	3.41*	2.30*	4.51*	5.17*
Spike length (cm)				
Conventional (CT)	7.8	7.6	7.7	7.8
Reduced (RT)	7.3	7.3	7.2	7.0
No-tillage (NT)	7.2	7.3	7.2	6.4
$LSD_{0.05}$	0.26*	0.19*	0.6	0.88*
Number of grains per spike (pcs.)				
Conventional (CT)	28.2	25.4	25.5	24.3
Reduced (RT)	24.9	24.2	23.7	21.5
No-tillage (NT)	24.2	23.4	22.7	17.8
$LSD_{0.05}$	2.10*	1.61*	3.8	5.86*
Grain weight per spike (g)				
Conventional (CT)	1.2	1.1	1.0	1.1
Reduced (RT)	1.0	0.9	0.9	0.8
No-tillage (NT)	1.0	0.9	0.9	0.7
$LSD_{0.05}$	0.08*	0.06*	0.1	0.23*

Explanations as in Tab. 2.
Source: own study.

GRAIN YIELD AND YIELD COMPONENTS

Grain yield was significantly affected by tillage system in each year of the study (Tab. 5). The highest average yield was obtained under CT (602.0 $g \cdot m^{-2}$), which was 16.7% higher than under RT

Table 5. Grain yield and yield components of spring wheat under different tillage systems

Tillage system	Years			
	2012	2016	2020	mean
Grain yield ($g \cdot m^{-2}$)				
Conventional (CT)	529.8	504.4	771.7	602.0
Reduced (RT)	458.0	434.1	655.5	515.9
No-tillage (NT)	384.7	374.6	501.1	420.1
$LSD_{0.05}$	18.5*	15.5*	14.8*	7.5*
Mean	457.6*	437.7*	642.8*	
Number of spikes ($pcs. \cdot m^{-2}$)				
Conventional (CT)	562.3	521.7	535.7	539.9
Reduced (RT)	519.2	470.9	508.1	499.4
No-tillage (NT)	431.9	439.3	435.5	435.6
$LSD_{0.05}$	17.9*	9.9*	0.8*	5.0*
Mean	504.5	477.3	493.1	
Number of grains per spike (pcs.)				
Conventional (CT)	21.5	26.4	29.6	25.8
Reduced (RT)	20.6	25.5	27.9	24.7
No-tillage (NT)	24.7	26.2	25.5	25.5
$LSD_{0.05}$	1.2*	3.1	1.0*	0.8*
Mean	22.3	26.0	27.7	
Thousand grain weight (g)				
Conventional (CT)	43.8	36.7	48.7	43.1
Reduced (RT)	42.8	36.2	46.2	41.7
No-tillage (NT)	36.1	32.5	45.2	37.9
$LSD_{0.05}$	3.6*	4.4	0.9*	1.4*
Mean	40.9	35.1	46.1	

Explanations as in Tab. 2.
Source: own study.

and 43.3% higher than under NT. Annual differences followed the same pattern, with CT outperforming RT by 15.7–17.7% and NT by 34.7–54.0%, depending on the year.

Among the yield components, spike number per square metre was the most responsive to tillage practice. Conventional tillage produced the highest spike density (539.9 spikes m^{-2}), which was 8.1% higher than under RT and 23.9% higher than under NT. The number of grains per spike and thousand grain weight (TGW) were also highest under CT, with TGW averaging 43.1 g, which represented increases of 3.4% over RT and 13.7% over NT.

EFFECT OF CANOPY STRUCTURAL TRAITS ON GRAIN YIELD

The relationship between canopy structural traits and grain yield varied across tillage systems (Tab. 6). Under CT, the correlation coefficient (r) indicated positive relationships between grain yield and both the number of shoots after tillering (r = 0.705) and the number of productive shoots (r = 0.758), suggesting that enhanced tillering contributed directly to yield formation. A moderate correlation was also observed between plant emergence and productive shoot number (r = 0.705), indicating a cascade effect in which initial stand establishment influenced final canopy density and productivity. Under RT, the number of productive shoots was strongly correlated with the number of shoots after tillering (r = 0.686) and moderately correlated with the number of emerged plants (r = 0.434). However, the direct correlation between productive shoots and grain yield was weaker than under CT, indicating that shoot survival or functionality may have been more variable under reduced soil disturbance. Under NT, the number of shoots after tillering showed the strongest correlation with the number of productive shoots (r = 0.769), suggesting that tillering plasticity remained important despite lower emergence rates.

EFFECT OF CANOPY ARCHITECTURE TRAITS ON GRAIN WEIGHT PER SPIKE

Relationships between canopy architecture traits and grain weight per spike varied depending on tillage system (Tab. 7). Under CT, strong positive correlations were observed between grain weight per spike and all measured traits. In particular, grain weight per spike was highly correlated with spike length (r = 0.620), number of grains per spike (r = 0.588), and single grain weight (r = 0.623). Under RT, the correlations were somewhat weaker but still

Table 6. Pearson's correlation coefficients linking grain yield to structural parameters of the spring wheat canopy under different tillage systems

Canopy structure traits	Tillage system														
	conventional (CT)					reduced (RT)					no-tillage (NT)				
	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5
Number of plants after emergence (pcs.·m^{-2}) – x_1	1.000					1.000					1.000				
Number of shoots after tillering (pcs.·m^{-2}) – x_2	0.705*	1.000				0.030	1.000				0.009	1.000			
Number of productive shoots (pcs.·m^{-2}) – x_3	0.758*	–0.104	1.000			0.434	0.686*	1.000			0.281	0.769*	1.000		
Number of sterile shoots (pcs.·m^{-2}) – x_4	–0.255	0.469	–0.006	1.000		0.046	0.074	0.367	1.000		0.375	0.281	0.444	1.000	
Grain yield (g·m^{-2}) – x_5	0.932*	0.791*	0.529	0.230	1.000	0.798*	0.616	0.104	–0.010	1.000	0.145	0.797*	0.691*	–0.149	1.000

Explanation: * = significant at α = 0.05.
Source: own study.

Table 7. Pearson's correlation coefficients between spike grain weight and canopy architecture parameters in spring wheat under different tillage systems

Canopy architecture traits	Tillage system														
	conventional (CT)					reduced (RT)					no-tillage (NT)				
	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5
Shoot length (cm) – x_1	1.000					1.000					1.000				
Spike length (cm) – x_2	0.619*	1.000				0.620*	1.000				0.657*	1.000			
Number of grains per spike (pcs.) – x_3	0.468*	0.468*	1.000			0.588*	0.623*	1.000			0.587*	0.562*	1.000		
Single grain weight (g) – x_4	0.483*	0.205*	0.349*	1.000		0.368*	0.276*	0.257*	1.000		0.346*	0.271*	0.212*	1.000	
Grain weight per spike (g) – x_5	0.529*	0.434*	0.922*	0.643*	1.000	0.616*	0.632*	0.910*	0.593*	1.000	0.640*	0.597*	0.930*	0.460*	1.000

Explanation: * = significant at α = 0.05.
Source: own study

notable. Grain weight per spike remained strongly associated with the number of grains per spike (r = 0.587) and was moderately associated with single grain weight (r = 0.562) and shoot length (r = 0.657). Under NT, the relationships were generally weaker and more variable. Grain weight per spike showed moderate correlations with spike length (r = 0.468) and single grain weight (r = 0.483), whereas its correlation with shoot length was weaker (r = 0.349).

DISCUSSION

The results demonstrate that soil tillage system significantly affects both structural and architectural traits of the spring wheat canopy, with effects carried through to grain yield. These findings are consistent with evidence that tillage intensity influences microenvironmental conditions critical for stand establishment, shoot development, and spike fertility, especially in spring cereals with short vegetative phases (Hobbs, Sayre and Gupta, 2008; Soane *et al.*, 2012; Pittelkow *et al.*, 2015).

The markedly higher plant density and shoot number observed under conventional tillage (CT) confirm the essential role of seedbed preparation in supporting rapid emergence and robust tillering. The more than 30% greater plant density under CT compared with no-tillage (NT) is consistent with long-term studies in temperate Europe, where insufficient soil loosening under conservation systems has been linked to restricted root growth and poor seed-to-soil contact (Rieger *et al.*, 2008; Soane *et al.*, 2012). The proportion of productive shoots and the frequency of multi-shoot plants were also higher under CT. Notably, the share of plants with three or more shoots was at least twice as high in conventional plots as in reduced- or no-tillage systems. These results are particularly relevant under increasingly erratic weather patterns, such as those encountered during the three growing seasons, when early-season drought or waterlogging can limit tillering in systems with reduced soil porosity (Rajala *et al.*, 2011; Slafer, Savin and Sadras, 2014). Although the dataset originates from earlier years, its agronomic relevance remains high. Current climate projections indicate increasing variability in early-season rainfall and soil moisture availability, reinforcing the importance of strong establishment and shoot productivity for yield resilience (Porter and Semenov, 2005; Fischer, 2011).

The analysis of canopy architecture showed that shoot and spike development were most advanced under CT, as indicated by greater shoot length, spike length, grain number per spike, and grain weight per spike. These traits probably benefited from improved root-zone conditions, including aeration, nutrient mineralisation, and water availability associated with deeper tillage (Tebrügge and Düring, 1999; Luo *et al.*, 2023). By contrast, NT showed pronounced limitations in spike development, especially in multi-shoot plants, where grain number per spike was reduced by up to 36% and spike weight by as much as 57%. These constraints suggest that NT can limit sink potential unless counterbalanced by targeted, long-term agronomic interventions, such as cultivar selection or increased seeding rates (Philipp *et al.*, 2018; Sułek and Cacak-Pietrzak, 2018). The consistently higher performance of multi-shoot plants under CT highlights the value of shoot plasticity and tiller efficiency in maximising spike productivity. This reinforces the concept that canopy architecture plays a key role in translating shoot number into yield, particularly under favourable conditions (Evers *et al.*, 2007; Gaju *et al.*, 2009).

Grain yield was highest under CT in each study year and was reduced by more than 30% under NT. These reductions reflect cumulative effects on plant establishment, tiller formation, shoot vigour, and spike fertility. Meta-analyses report similar yield penalties for NT systems on light-textured soils in Central Europe, where spring rainfall variability and shallow rooting depth limit crop performance (Morris *et al.*, 2010; Pittelkow *et al.*, 2015). Although NT offers long-term benefits for soil health and erosion control, its agronomic performance under specific soil-climate conditions can remain limited. In regions with compacted subsoils and erratic precipitation, for which Central Poland is an illustrative example, CT may still provide short- to medium-term yield advantages (Kassam *et al.*, 2009; Woźniak and Rachoń, 2020). Importantly, the observed reduction in thousand grain weight under NT suggests not only fewer spikes per square metre but also less efficient grain filling. This could result from impaired nutrient uptake or shortened grain-filling duration, both of which warrant further investigation under NT (Fischer, 2011; Liu *et al.*, 2023).

The strong correlations between canopy structural traits and grain yield, particularly under CT and RT, underscore the critical role of early crop architecture in yield formation. In contrast, weaker correlations under NT point to a yield formation process that relies more heavily on compensatory mechanisms, such as secondary tillering, than on optimal initial canopy density. Similarly, positive correlations between spike-related traits and grain weight per spike confirm that canopy architecture should be considered alongside canopy structure when evaluating tillage effects on yield. These results support the view that tillage is not solely a soil management practice but also a tool for shaping the functional design of the crop canopy (Gaju *et al.*, 2009; Křen *et al.*, 2013).

Under ongoing climate instability, tillage strategies need to be adapted to maintain canopy functionality under stress. While NT remains an environmentally attractive option, its agronomic performance should be supported through complementary approaches, including enhanced fertilisation strategies, strip tillage, high-vigour cultivars, and precision seed placement (Tebrügge and Düring, 1999; Zheng *et al.*, 2014).

CONCLUSIONS

This study demonstrated that tillage system is a key driver of spring wheat canopy formation, directly shaping structural and architectural traits that determine grain yield under temperate climatic conditions. Conventional tillage (CT) consistently enhanced stand establishment, increased plant density by more than 30% compared with no-tillage (NT), and promoted the development of productive tillers and larger spikes. These effects resulted in the highest grain yield, averaging 602 $g \cdot m^{-2}$, which was 16–18% higher than under reduced tillage (RT) and more than 40% higher than under NT.

The higher canopy density and spike fertility observed under CT confirm the importance of well-loosened soil for early crop establishment and tiller survival. RT produced intermediate values for canopy traits and yield components, indicating that it can serve as a viable compromise between productivity and soil protection when supported by optimised fertilisation and appropriate cultivar selection. By contrast, NT limited emergence and tillering capacity, resulting in fewer spikes per square metre and lower grain weight per spike. Yield penalties exceeding 30% were mainly associated with weaker canopy structure and reduced sink capacity.

Overall, the results show that long-term tillage management not only determines soil conditions but also shapes the functional design of the crop canopy. Integrating canopy-level assessment into tillage studies can improve understanding of yield formation processes and support the development of sustainable crop management strategies adapted to variable climatic conditions.

CONFLICTS OF INTEREST

All authors declare that they have no conflict of interest.

REFERENCES

Barut, Z.B. and Çelik, I. (2010) "Different tillage systems affect plant emergence, stand establishment and yield in wheat-corn rotation," *Philippine Agricultural Scientist*, 93(4), pp. 392–398.

Cárcer de, P.S. *et al.* (2019) "Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties," *Soil and Tillage Research*, 190, pp. 209–219. Available at: https://doi.org/10.1016/j.still.2019.01.012.

Carr, P.M., Gramig, G.G. and Liebig, M.A. (2013) "Impacts of organic zero tillage systems on crops, weeds, and soil quality," *Sustainability*, 5(7), pp. 3172–3201. Available at: https://doi.org/10.3390/su5073172.

Chataut, G. *et al.* (2023) "Greenhouse gases emission from agricultural soil: A review," *Journal of Agriculture and Food Research*, 11, 100533. Available at: https://doi.org/10.1016/j.jafr.2023.100533.

Dhanda, S.S. and Sethi, G.S. (2002) "Tolerance to drought stress among selected Indian wheat cultivars," *Journal of Agricultural Science*, 139(3), pp. 319–326. Available at: https://doi.org/10.1017/S0021859602002526.

Dzieżyc, J., Nowak, L. and Panek, K. (1987) "Dekadowe wskaźniki potrzeb opadowych roślin uprawnych w Polsce [The decade indicators of the rainfall needs of the crops cultivated in Poland]," *Zeszyty Problemowe Postępów Nauk Rolniczych*, 314, pp. 11–33.

Evers, J.B. *et al.* (2007) "An architectural model of spring wheat: evaluation of the effects of population density and shading on model parameterization and performance," *Ecological Modelling*, 200(3–4), pp. 308–320. Available at: https://doi.org/10.1016/j.ecolmodel.2006.07.042.

Farooq, M. *et al.* (2011) "Crop yield and weed management in rainfed conservation agriculture," *Soil and Tillage Research*, 117, pp. 172–183. Available at: https://doi.org/10.1016/j.still.2011.10.001.

Fischer, R.A. (2011) "Wheat physiology: A review of recent developments," *Crop and Pasture Science*, 62(2), pp. 95–114. Available at: https://doi.org/10.1071/CP10344.

Gaju, O. *et al.* (2009) "Relationships between large-spike phenotype, grain number, and yield potential in spring wheat," *Crop Science*, 49(3), pp. 961–973. Available at: https://doi.org/10.2135/cropsci2008.05.0285.

Hobbs, P.R., Sayre, K. and Gupta, R. (2008) "The role of conservation agriculture in sustainable agriculture," *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), pp. 543–555. Available at: https://doi.org/10.1098/rstb.2007.2169.

Huang, G. *et al.* (2024) "Effect of plant architecture on the responses of canopy temperature and water use to population density in winter wheat," *Crop Science*, 64(3), pp. 1874–1886. Available at: https://doi.org/10.1002/csc2.21220.

Iqbal, M.M. *et al.* (2022) "Performance of wheat cultivars under different tillage and crop establishment methods," *International Journal of Plant Production*, 16(2), pp. 287–297. Available at: https://doi.org/10.1007/s42106-021-00174-0.

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 edn. Vienna: International Union of Soil Sciences. Available at: https://files.isric.org/public/documents/WRB_fourth_edition_2022-12-18.pdf (Accessed: April 15, 2025).

Jalli, M. *et al.* (2021) "Effects of crop rotation on spring wheat yield and pest occurrence in different tillage systems: a multi-year experiment in Finnish growing conditions," *Frontiers in Sustainable Food Systems*, 5, 647335. Available at: https://doi.org/10.3389/fsufs.2021.647335.

Karlen, D.L. *et al.* (2013) "Thirty-year tillage effects on crop yield and soil fertility indicators," *Soil and Tillage Research*, 130, pp. 24–41. Available at: https://doi.org/10.1016/j.still.2013.02.003.

Kassam, A. *et al.* (2009) "The spread of conservation agriculture: justification, sustainability and uptake," *International Journal of Agricultural Sustainability*, 7(4), pp. 292–320. Available at: https://doi.org/10.3763/ijas.2009.0477.

Kiss, T. *et al.* (2018) "Associations between plant density and yield components using different sowing times in wheat (*Triticum aestivum* L.)," *Cereal Research Communications*, 46(2), pp. 211–220. Available at: https://doi.org/10.1556/0806.45.2017.069.

Korbas, M., Horoszkiewicz-Janka, J. and Mrówczyński, M. (eds.) (2017) *Metodyka integrowanej ochrony pszenicy ozimej i jarej dla doradców [Methodology of integrated protection of winter and spring wheat for advisors]*. Poznań: Instytut Ochrony Roślin – Państwowy Instytut Badawczy.

Křen, J. *et al.* (2013) "Cereal canopy structure – its assessment and use in efficient crop management," in M.D. Matovic (ed.) *Biomass now – Sustainable growth and use*. IntechOpen. Available at: http://dx.doi.org/10.5772/54528.

Liu, K. *et al.* (2023) "Improving photosynthesis and grain yield in wheat through ridge–furrow ratio optimization," *Agronomy*, 13(9), 2413. Available at: https://doi.org/10.3390/agronomy13092413.

Lonbani, M. and Arzani, A. (2011) "Morpho-physiological traits associated with terminal drought stress tolerance in triticale and wheat," *Agronomy Research*, 9(1–2), pp. 315–329.

López-Bellido, R.J. *et al.* (2023) "Faba bean (*Vicia faba* L.) response to tillage and soil residual nitrogen in a continuous rotation with wheat (*Triticum aestivum* L.) under rainfed Mediterranean conditions," *Agronomy Journal*, 95(5), pp. 1253–1261. Available at: https://doi.org/10.2134/agronj2003.1253.

Luo, X. *et al.* (2023) "Deciphering spike architecture formation towards yield improvement in wheat," *Journal of Genetics and Genomics*, 50(11), pp. 835–845. Available at: https://doi.org/10.1016/j.jgg.2023.02.015.

Machado, S., Rhinhart, K. and Petrie, S. (2006) "Long-term cropping system effects on carbon sequestration in eastern Oregon," *Journal of Environmental Quality*, 35(4), pp. 1548–1553. Available at: https://doi.org/10.2134/jeq2005.0201.

Morris, N.L. *et al.* (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 and Tillage*

Research, 108(1–2), pp. 1–15. Available at: https://doi.org/10.1016/j.still.2010.03.004.

Mwendwa, J.M. *et al.* (2020) "Evaluation of commercial wheat cultivars for canopy architecture, early vigour, weed suppression, and yield," *Agronomy*, 10(7), 983. Available at: https://doi.org/10.3390/agronomy10070983.

Paulus, S. *et al.* (2014) "High-precision laser scanning system for capturing 3D plant architecture and analysing growth of cereal plants," *Biosystems Engineering*, 121, pp. 1–11. Available at: https://doi.org/10.1016/j.biosystemseng.2014.01.010.

Philipp, N. *et al.* (2018) "Grain number and grain yield distribution along the spike remain stable despite breeding for high yield in winter wheat," *PLoS One*, 13(10), e0205452. Available at: https://doi.org/10.1371/journal.pone.0205452.

Pittelkow, C.M. *et al.* (2015) "Productivity limits and potentials of the principles of conservation agriculture," *Nature*, 517(7534), pp. 365–368. Available at: https://doi.org/10.1038/nature13809.

Porter, J.R. and Semenov, M.A. (2005) "Crop responses to climatic variation," *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1463), pp. 2021–2035. Available at: https://doi.org/10.1098/rstb.2005.1752.

Rajala, A. *et al.* (2011) "Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley," *Journal of Agronomy and Crop Science*, 197(2), pp. 103–112. Available at: https://doi.org/10.1111/j.1439-037X.2010.00449.x.

Rieger, S. *et al.* (2008) "Growth, yield, and yield components of winter wheat and the effects of tillage intensity, preceding crops, and N fertilisation," *European Journal of Agronomy*, 28(3), pp. 405–411. Available at: https://doi.org/10.1016/j.eja.2007.11.006.

Selyaninov, G.T. (1928) "On agricultural climate valuation," *Proceedings of Agricultural Methodology*, 20, pp. 165–177.

Shahzad, M. *et al.* (2016) "Impact of different crop rotations and tillage systems on weed infestation and productivity of bread wheat," *Crop Protection*, 89, pp. 161–169. Available at: https://doi.org/10.1016/j.cropro.2016.07.019.

Slafer, G.A., Savin, R. and Sadras, V.O. (2014) "Coarse and fine regulation of wheat yield components in response to genotype and environment," *Field Crops Research*, 157, pp. 71–83. Available at: https://doi.org/10.1016/j.fcr.2013.12.004.

Soane, B.D. *et al.* (2012) "No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment," *Soil and Tillage Research*, 118, pp. 66–87. Available at: https://doi.org/10.1016/j.still.2011.10.015.

Steponavičienė, V. *et al.* (2024) "Long-term effects of different tillage systems and their impact on soil properties and crop yields," *Agronomy*, 14(4), 870. Available at: https://doi.org/10.3390/agronomy14040870.

Sułek, A. and Cacak-Pietrzak, G. (2018) "The influence of production technology on yield and selected quality parameters of spring wheat cultivars," *Research for Rural Development*, 2, pp. 42–48. Available at: https://doi.org/10.22616/rrd.24.2018.049.

Sułek, A., Wyzińska, M. and Cacak-Pietrzak, G. (2019) "Impact of tillage on yield and quality traits of grains of spring wheat cultivars," *Engineering for Rural Development*, 18, pp. 600–606.

Tebrügge, F. and Düring, R.A. (1999) "Reducing tillage intensity – a review of results from a long-term study in Germany," *Soil and Tillage Research*, 53(1), pp. 15–28. Available at: https://doi.org/10.1016/S0167-1987(99)00073-2.

TIBCO Software Inc. (2017) *Statistica (Data Analysis Software System), Version 13*. Palo Alto, CA: TIBCO Software Inc.

Tørresen, K.S. *et al.* (2003) "Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield," *Crop Protection*, 22(1), pp. 185–200. Available at: https://doi.org/10.1016/S0261-2194(02)00145-X.

Woźniak, A. and Rachoń, L. (2020) "Effect of tillage systems on the yield and quality of winter wheat grain and soil properties," *Agriculture*, 10(9), 405. Available at: https://doi.org/10.3390/agriculture10090405.

Zheng, C.Y. *et al.* (2014) "Effects of tillage practices on water consumption, water use efficiency and grain yield in wheat field," *Journal of Integrative Agriculture*, 13(11), pp. 2378–2388.

Zhou, H. *et al.* (2021) "Determination of wheat spike and spikelet architecture and grain traits using X-ray Computed Tomography imaging," *Plant Methods*, 17, pp. 1–9. Available at: https://doi.org/10.1186/s13007-021-00726-5.