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Effect of strip-till and cultivar on photosynthetic parameters and grain yield of winter wheat

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Abstract. For economic, environmental, and climatic reasons, soil cultivation methods without the use of a plough have became increasingly popular in recent decades. As research has shown, their impact on the growth and yield of crops is not always positive, especially when direct sowing is used. Recently, a new solution in the field of tillage has appeared which involves loosening the soil only within the sowing zone, which is called strip till. In the research presented in this work, this method was used for various cultivars of winter wheat on uncultivated stubble, but also after cultivation of the stubble just after harvest of a forecrop. The aim of the paper was to define the impact of the aforementioned factors on the parameters of photosynthesis, leaf area index, and water use efficiency. The range of soil cultivation after the harvest of the forecrop and cultivars influenced significantly the measured photosynthesis parameters. The impact of the cultivation method and variety on water use efficiency was small, although it should be noted that limiting the intensity of cultivation after the forecrop harvest had a temporary positive impact on the flag leaf phase. The winter wheat cultivar had an impact on the yield obtained: Formacja (0.44 t ha^{-1}) and Metronom (0.37 t ha^{-1}) yielded higher than Desamo. In the case of plough tillage, the yield was higher than in the case of minimum tillage and no tillage. Given the economic and environmental benefits associated with reduced fuel consumption, no tillage with a relatively slightly lower yield may be an alternative to the use of plough tillage.

Keywords: soil cultivation, strip-till, photosynthesis parameters, water use efficiency, winter wheat, cultivar

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1. INTRODUCTION

Soil tillage significantly influences the physical, chemical, and biological properties of the soil (Ding *et al.*, 2020; Gondal *et al.*, 2021; Khan *et al.*, 2023; Douibi *et al.*, 2024). The way it is performed has undergone major changes in recent years. Above all, reduced tillage technologies have begun to gain popularity (Su *et al.*, 2021). The most severe tillage restrictions are associated with zero-tillage, in which the soil is not tilled at all and sowing is carried out using disc coulters that cut the moisture-deficient soil to introduce the seed to a certain depth. Research has shown that complete no-till generally leads to large yield decreases (Rieger *et al.*, 2008; Brennan *et al.*, 2014). In recent years, the implementation of tillage simplification, in which only the soil in the sowing strip is cultivated while the rest remains uncultivated, has become increasingly popular. This is referred to as strip-till (Jaskulska *et al.*, 2020). Strip-till cultivation is increasingly popular and has many advantages. It reduces labour and fuel consumption, as soil cultivation, fertiliser application, and sowing can be carried out in a single pass. This has a beneficial effect of reducing carbon dioxide emissions into the atmosphere (Jaskulski *et al.*, 2023). An additional positive effect is also the increase in organic matter content and the increase in soil carbon sequestration as well as the reduction in nitrogen losses related to leaching into deeper soil layers (Dębska *et al.*, 2020; Jaskulska *et al.*, 2023; Jaskulski *et al.*, 2023). The beneficial effect of applied strip-till is also due to the increased microbial activity of the soil (Jaskulska *et al.*, 2023; Jaskulski *et al.*, 2023). The use of this cultivation method creates good conditions for plant emergence and root system development. To date, few studies have been conducted to determine the role of strip-tillage in shaping photosynthetic parameters in crop plants. Single reports in this area indicate that this type of tillage can have positive effects on plant growth. Wheat sowing with a strip-till unit can be carried out directly into uncultivated stubble, but some authors have also introduced treatments in their studies where such sowing was carried out into previously cultivated soil, which sometimes had a positive effect on the yield (Saldukaitė-Sribikė *et al.*, 2022). Various authors have attempted to determine the interaction between the extent of tillage and other agrotechnical factors including, in particular, the genetic factor, *i.e.* the choice of a particular cultivar characterised by a specific yield potential (Mądry *et al.*, 2017; Iwańska *et al.*, 2020). The different response of cultivars to agronomic factors may be due to their genetic resistance to biotic and abiotic stresses (Trethowan *et al.*, 2012; Egea-Gilabert *et al.*, 2021; Niedbała *et al.*, 2022). Research has shown that tillage can modify these stresses to a greater or lesser extent, which is reflected in the intensity of physiological processes (Ali *et al.*, 2018b; Dong *et al.*, 2019; Yang *et al.*, 2021; Sun *et al.*, 2023). This may be related to the cultivation of the soil itself, which creates various conditions for the development of the root system. The diverse process of photosynthesis may also be influenced by the specific situation related to the sowing of plants that are placed in sowing strips, but plants lean towards uncultivated strips to take advantage of greater availability of light, which may also increase photosynthesis intensity (Moroyoqui-Parra *et al.*, 2023). Unfortunately, there is little knowledge about the impact of strip-tillage on these processes.

The aim of the study was to compare the photosynthesis parameters of selected winter wheat cultivars grown in strip-till compared to three different types of post-harvest tillage (ploughed tillage, stubble discing, strip-tillage). It was hypothesized that the genetic factor would strongly differentiate the values of photosynthesis parameters, while the difference due to tillage would be smaller.

2. 2. MATERIALS AND METHODS

2.1. Characteristics of field conditions and experimental set-up

In order to verify the adopted research hypothesis, field tests were carried out in three growing seasons: 2018/2019, 2019/2020, 2020/2021 at the Agricultural Experimental Station Kępa – Osiny (51°27′ N; 22°2′ E) belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy. The soil was defined as black earth proper, included in the good wheat complex. The forecrop was winter wheat. The experiment was set up in a split-block arrangement with mirror image, in 4 replications according to Fig. 1. The size of a single test plot was 225 m^2 (9 × 25 m).

The first factor of the field experiment was the different ranges of tillage before sowing:

1) ploughed tillage + strip-tillage (PT) (Fig. 2a),
2) stubble discing + strip-tillage (SD) (Fig. 2b),
3) strip-tillage (ST) (Fig. 2c).

The second factor was wheat cultivars differing considerably in origin (different breeders). The selection of specific cultivars took into account all available varietal

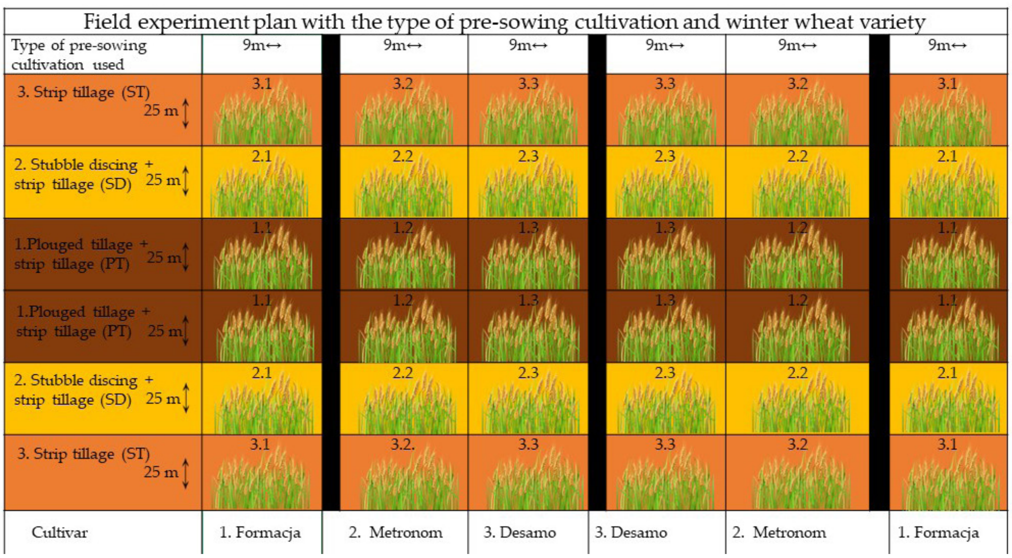


Fig. 1. Plan of the experimental setup with the marked location of the factors: tillage and variety of winter wheat.

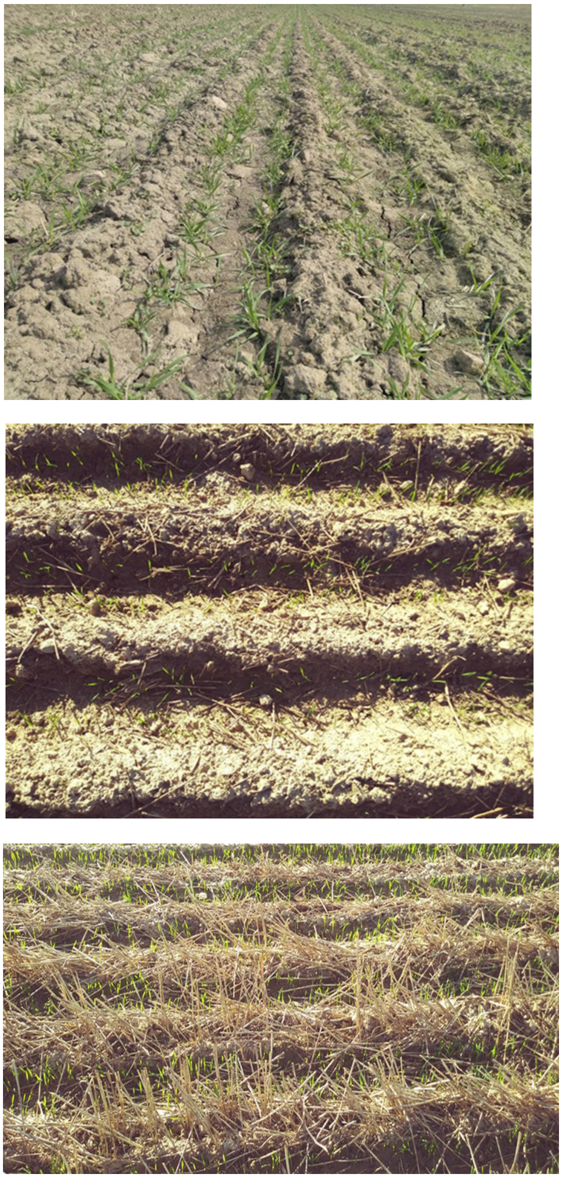
a)
b)
c)


Fig. 2. Image from an experimental plot: a) plouged tillage + strip - tillage (PT), b) stubble discing + strip-tillage (SD), and c) strip-tillage (ST).

characteristics related mainly to the resistance of the cultivars to biotic and abiotic stresses. As a result, 3 cultivars were selected for the study:

1) Formacja (Poznańska Hodowla Roślin) – quality class A.
2) Metronom (Top Farms) – quality class A.
3) Desamo (DANKO breeding) – quality class A.

Strip-till cultivation was then used in each experimental treatment along with wheat sowing. Wheat sowings were carried out in all objects at the optimal or permissibly delayed date (at the beginning of October) using a strip-tillage unit C MZURI Valtra, which loosened the soil in the sowing strip to a depth of 20 cm. The width of the seed strip was 12.cm. The sowing rate was 385 grains per m^2.

Table 1. Characteristics of soil chemical properties

Parameter		Value (from-to)
pH in KCl		5.7-6.2
P_2O_5		20.3-24.6
K_2O	(mg 100 g^{-1} soil)	27.4-27.7
Mg		9.9-12.3

The soil chemical composition is shown in Table 1. Phosphorus and potassium fertilisation adapted to soil abundance was applied pre-sowing at 36 kg P_2O_5 and 54 K_2O kg ha^{-1}. Nitrogen fertilisation at a total dose of 160 kg ha^{-1} was split into three doses:

1) 70 kg ha^{-1} N at the tillering stage,
2) 50 kg ha^{-1} N at the stalk shooting stage,
3) 40 kg ha^{-1} N at the beginning of the earing stage.

2.2. Meteorological conditions

The meteorological conditions during the vegetation period were characterized by mean daily temperature (°C) and precipitation (mm) and comparison of these parameters to the multi-year average (Table 2). The three-year research period was characterized by variability of weather conditions. Large differences in temperature were mainly recorded in the autumn and winter periods, while the thermal conditions in spring were similar and did not differ significantly from the long-term average. The amount of rainfall in individual seasons varied greatly. In each of the seasons, there were periods with a greater or lesser lack of rainfall, but in general, the rainfall totals in each season were relatively large, especially in the third year of research, 2020/2021, when the rainfall in the period before the harvest significantly exceeded the long-term norm. In addition, the climatic water balance index (Table 3), which determines the difference between precipitation and evapotranspiration, was used to characterize the weather conditions. It is calculated according to the Eq. (1) (Łabędzki and Bąk, 2004):

$$KBW = P - E, \qquad (1)$$

where: P – total precipitation, E – evapotranspiration.

In individual periods of measuring the climatic water balance, its significant variability was found. The largest negative balance was recorded in 2019 (-364). The remaining two years of research also had different values. In 2020, the climatic water balance had the most favourable value (-161). In 2021, the total climatic water balance was -281.

2.3. Photosynthesis parameters

Photosynthesis measurements were made with a CIRAS-2 Portable Infrared Gas Exchange Analyser Type CIRAS-2 Portable Photosynthesis System (Hitchin, Herts., UK). Using this device, the following parameters were measured:

Table 2. Meteorological conditions during the study

Month	Air temperature (°C)				Precipitation (mm)			
	Growing season			Multi-year average	Growing season			Multi-year average
	2018/2019	2019/2020	2020/2021	1981-2010	2018/2019	2019/2020	2020/2021	1981-2010
IX	15.5	14.4	14.9	13.3	48.0	57.8	102.0	55.0
X	10.0	10.8	10.4	8.0	40.5	33.5	90.0	44.0
XI	4.2	6.4	5.1	2.7	8.9	31.4	14.0	39.0
XII	0.9	3.1	1.7	-1.4	61.0	47.9	19.0	37.0
I	-2.4	1.7	-1.4	-3.3	62.0	27.1	51.0	31.0
II	2.9	3.4	-2.7	-2.3	15.2	56.5	38.0	30.0
III	5.7	4.7	2.8	1.6	20.9	16.7	12.0	30.0
IV	10.0	8.9	6.9	8.7	39.0	14.4	50.0	39.0
V	13.9	11.9	12.9	14.5	69.0	93.9	61.0	58.0
VI	22.7	19.1	20.0	17.2	37.0	159.0	53.0	65.0
VII	19.4	19.3	22.2	19.5	71.0	31.9	110.0	80.0
VIII	20.4	20.3	17.1	17.8	94.3	95.5	219.0	87.0

Table 3. Climatic water balance in selected months during the study period (mm)

Year	Month				
	IV	V	VI	VII	IV-VII
2019	-77	-135	-152	-209	-142
2020	-86	-34	-41	-86	-42
2021	-117	-104	-60	-36	-88

• net photosynthetic efficiency *Pn* (μmol m^{-2} s^{-1}),
• transpiration efficiency (mmol m^{-2} s^{-1}),
• stomatal conductivity gs (mmol H_2O m^{-2} s^{-1}),
• intracellular carbon dioxide concentration Ci (μmol CO_2 m^{-2} s^{-1}).

These measurements were carried out on the flag leaf at three dates: at the flag leaf stage (BBCH 39), the start of earing (BBCH 51), and after earing (at the BBCH 65 stage). The light intensity of 1000 PAR (μmol m^{-2} s^{-1}), a constant supply of carbon dioxide equal to 370 ppm (μmol CO_2 mol^{-1} air), humidity equal to the ambient humidity, and air temperature equal to +25°C were maintained in the measuring chamber of the apparatus. For each experimental plot, measurements were taken in the middle of the plot on four randomly selected plants. Figure 3 illustrates how the measurement was carried out. In addition, the photosynthesis measurements obtained were used to calculate water use efficiency (*WUE*) according to the Eq. (2):

$$WUE = \frac{Pn}{E}, \tag{2}$$

Pn – net photosynthetic efficiency, *E* – transpiration efficiency.

Fig. 3. Measurement of photosynthetic parameters under field conditions.

2.4. LAI

The leaf area index (LAI) was determined using the LAI 2000 Plant Canopy Analyzer on every plot. The measurements were done three times on the same dates as the photosynthesis measurements and additionally at the stalk shooting stage (BBCH 32-39). A single LAI measurement consisted of two measurements over the canopy and eight in the canopy on the ground surface. The quality of these measurements was controlled on an ongoing basis and if an error of 5% was exceeded, the measurement was eliminated from the dataset and taken again.

2.5. Grain harvest and yield

The grain was harvested with a harvester combine at full grain maturity in the beginning of August. The grain yield from the plots was converted per ha at 15% moisture content.

2.6. Statistical analyses

The results were analyzed using analysis of variance ANOVA, and the significance of the means at $p \leq 0.05$ was verified using the Tukey test with STATISTICA ver. 13.1 software (StatSoft, Inc., Tulsa, OK, USA).

3. RESULTS

In the study, the tillage method significantly influenced the photosynthetic activity of wheat plants (Table 4). In each phase, the highest net photosynthesis value was observed in the ploughed field. The differences in this trait between the other two tillage methods were smaller than in the plough tillage variant. However, at the flag leaf stage, a significantly higher net photosynthetic intensity was found in the strip-tillage (ST) relative to the reduced tillage object (SD). The effect of the cultivar on shaping net photosynthesis was observed at the flag leaf stage and at the early earing stage, when the significantly highest value for this trait was observed in the Formacja cultivar and the lowest in the Desamo cultivar. At the BBCH 65 stage, the intervarietal differences for the trait in question were no longer significant. Large differences in net photosynthesis were observed between the years of the study. Irrespective of the growth stage, by far the highest value for this parameter was observed in 2021 and the lowest in 2020.

Table 4. Net photosynthesis of *Pn* ($\mu mol\ m^{-2}\ s^{-1}$) at different developmental stages according to cropping system, cultivar and years of study

Specification	Development phase		
	Flag leaf	Beginning of earing	Full flowering
Cultivation system			
Ploughing (CT)	13.8^{a}	14.1^{a}	14.4^{a}
Simplified (MT)	11.7^{c}	12.8^{b}	13.9^{b}
Zero (TS)	12.7^{b}	12.5^{b}	13.9^{b}
Cultivar			
Formacja	13.3^{a}	13.7^{a}	14.1^{a}
Metronom	12.6^{b}	13.2^{ab}	14.2^{a}
Desamo	12.3^{b}	12.5^{b}	14.0^{a}
Year			
2019	13.6^{b}	13.5^{b}	15.2^{a}
2020	10.4^{c}	10.7^{c}	11.1^{b}
2021	14.2^{a}	15.2^{a}	15.8^{a}
Factor interaction			
T	***	***	*
C	***	***	ns
Y	***	***	***
T × C	ns	**	ns
T ×Y	***	***	ns
C ×Y	*	ns	*
T ×C ×Y	ns	**	ns

Different letters (a-c) mean significant difference ($\alpha = 0.05$), according to ANOVA and Tukey's test. Significant difference *≤0.05, **≤0.01, ***<0.001, and ns – not significant differents, T – tillage, C – cultivar, Y – year.

Table 5. Transpiration ($mmol\ m^{-2}\ s^{-1}$) at different developmental stages according to cropping system, cultivar and years of study

Specification	Development phase		
	Flag leaf	Beginning of earing	Full flowering
Cultivation system			
Ploughed tillage + strip-tillage (PT)	2.3^{a}	2.3^{a}	2.1^{a}
Stubble discing + strip-tillage (SD)	2.0^{b}	1.9^{b}	2.0^{a}
Strip-tillage (ST)	2.2^{a}	2.1^{a}	2.0^{a}
Cultivar			
Formacja	2.2^{a}	2.1^{b}	2.1^{a}
Metronom	2.2^{a}	2.2^{a}	2.1^{a}
Desamo	2.0^{b}	2.0^{c}	2.0^{a}
Year			
2019	2.8^{a}	2.8^{a}	2.3^{a}
2020	1.7^{c}	1.4^{c}	1.8^{c}
2021	2.0^{b}	2.1^{b}	2.0^{b}
Factor interaction			
T	***	***	ns
C	ns	*	ns
Y	***	***	***
T × C	**	ns	***
T ×Y	***	***	ns
C ×Y	ns	*	ns
T ×C ×Y	ns	***	ns

Explanations as in Table 4.

The transpiration intensity significantly depended on the tillage method at the first two phases (flag leaf and beginning of earing). The value of this trait was significantly higher in the plough (PT) and strip-tillage (ST) treatments than in the reduced tillage (SD). The value of transpiration did not depend significantly on tillage (Table 5). The varietal factor clearly differentiated the wheat transpiration intensity, with the lowest value of this trait found in the Desamo cultivar regardless of the plant growth stage. It should be noted, however, that at the full flowering stage, the differences in transpiration were only trendlike and statistically insignificant. Considerable variability in transpiration was observed in the individual years of the study. The highest transpiration intensity, regardless of the developmental stage of the wheat plants, was found in 2019, and the lowest in 2020.

The effect of the tillage method on stomatal conductance (gs) was dependent on the growth stage. At the flag leaf stage, this trait was significantly lowest in the reduced tillage conditions. Such a relationship was also maintained at the early earing stage, but at the next stage, the reverse relationship was already found – significantly the highest value of stomatal conductance was found under reduced tillage SD (Table 6). The cultivar factor also significantly modified the gs values. At the flag leaf stage, the cultivar Metronom showed a significantly higher gs value relative to the cultivars Formacja and Desamo. At the early earing stage, the cultivar Metronom showed the highest gs value, while Desamo the lowest. At full earing, the cultivar Formacja had the highest gs value, while the cultivar Metronom had the lowest. The gs value was also significantly influenced by the years. Regardless of the growth stage, by far the highest gs values were found in 2019.

The post-harvest tillage method played a significant role in shaping the Intracellular CO_2 concentration (Ci) at the flag leaf stage only, when the highest value of this trait was found in the strip-tillage (ST) treatment and the lowest in the plough tillage (PT) treatment (Table 7). At the later stages, a similar but statistically not proven relationship was found. The varietal factor did not significantly differentiate the Ci values. Relatively high year-to-year variability in the intracellular CO_2 concentration was observed at different growth stages. At the flag leaf and full flowering, the highest value for this trait was found in 2020 and at beginning of earing in 2021.

Water use efficiency (WUE) depended significantly on the tillage method, which was only revealed at the early earing stage, with the highest value of this parameter found in treatments with reduced tillage (SD) (Table 8). The effect of the cultivar on *WUE* was not large, but was significant at the early earing stage – the highest value having been recorded in the Formacja cultivar. Very high variability of *WUE* was found depending on the year. The highest values of this parameter were found in 2021.

Irrespective of the testing date, the highest LAI values were found in the ploughed field. The differences in the value of this trait between the other two tillage methods were small and statistically insignificant. The role of the cultivar in shaping the leaf index was not statistically significant

Table 6. Stomatal conductance gs (mmol H_2O m^{-2} s^{-1}) at different developmental stages according to cropping system, cultivar and years of study

Specification	Development phase		
	Flag leaf	Beginning of earing	Full flowering
Cultivation system			
Ploughed tillage + strip-tillage (PT)	0.263^{a}	0.270^{ab}	0.261^{b}
Stubble discing + strip-tillage (SD)	0.227^{b}	0.263^{b}	0.281^{a}
Strip-tillage (ST)	0.271^{a}	0.285^{a}	0.252^{b}
Cultivar			
Formacja	0.249^{b}	0.270^{b}	0.277^{a}
Metronom	0.265^{a}	0.298^{a}	0.258^{b}
Desamo	0.249^{b}	0.250^{c}	0.261^{ab}
Year			
2019	0.396^{a}	0.422^{a}	0.355^{a}
2020	0.155^{c}	0.241^{b}	0.280^{b}
2021	0.213^{b}	0.155^{c}	0.161^{c}
Factor interaction			
T	***	*	***
C	ns	***	*
Y	***	***	***
T × C	ns	**	ns
T ×Y	**	***	***
C ×Y	ns	***	ns
T ×C ×Y	ns	***	***

Explanations as in Table 4.

Table 7. Intercellular concentration of CO_2 - Ci (μmol CO_2 m^{-2} s^{-1}) at different developmental stages according to cropping system, cultivar and year of study

Specification	Development phase		
	Flag leaf	Beginning of earing	Full flowering
Cultivation system			
Ploughed tillage + strip-tillage (PT)	181^{c}	225^{a}	198^{a}
Stubble discing + strip-tillage (SD)	198^{b}	235^{a}	197^{a}
Strip-tillage (ST)	219^{a}	241^{a}	204^{a}
Cultivar			
Formacja	195^{a}	235^{a}	199^{a}
Metronom	203^{a}	237^{a}	200^{a}
Desamo	200^{a}	229^{a}	199^{a}
Year			
2019	179^{c}	180^{c}	193^{b}
2020	223^{a}	244^{b}	216^{a}
2021	196^{b}	277^{a}	190^{b}
Factor interaction			
T	***	***	ns
C	ns	*	ns
Y	***	***	***
T × C	***	ns	ns
T ×Y	***	***	***
C ×Y	ns	ns	*
T ×C ×Y	ns	ns	***

Explanations as in Table 4.

Table 8. Water use efficiency (*WUE*) at different developmental stages according to cropping system, cultivar and year of study

Specification	Development phase		
	Flag leaf	Beginning of earing	Full flowering
Cultivation system			
Ploughed tillage + strip-tillage (PT)	6.0^{a}	6.1^{b}	6.9^{a}
Stubble discing + strip-tillage (SD)	5.9^{a}	6.7^{a}	7.0^{a}
Strip-tillage (ST)	5.8^{a}	6.0^{b}	7.0^{a}
Cultivar			
Formacja	6.0^{a}	6.5^{b}	6.7^{a}
Metronom	5.7^{a}	6.0^{a}	6.8^{a}
Desamo	6.2^{a}	6.3^{a}	7.0^{a}
Year			
2019	4.9^{c}	4.8^{b}	6.6^{b}
2020	6.1^{b}	7.6^{a}	6.2^{b}
2021	7.1^{a}	7.2^{a}	7.9^{a}
Factor interaction			
T	ns	***	ns
C	ns	*	ns
Y	***	***	***
T × C	**	ns	***
T ×Y	**	ns	*
C ×Y	ns	ns	**
T ×C ×Y	ns	**	ns

Explanations as in Table 4.

Table 9. LAI values at different developmental stages according to cropping system, cultivar and year of study

Specification	Development phase			
	Shooting	Flag leaf	Beginning of earing	Full flowering
Cultivation system				
Ploughed tillage + strip-tillage (PT)	1.74^{a}	2.21^{a}	3.58^{a}	4.23^{a}
Stubble discing + strip-tillage (SD)	1.55^{a}	2.10^{a}	3.46^{a}	3.87^{a}
Strip-tillage (ST)	1.64^{a}	2.15^{a}	3.33^{a}	3.93^{a}
Cultivar				
Formacja	1.78^{a}	2.10^{a}	3.37^{a}	3.98^{a}
Metronom	1.77^{a}	2.19^{a}	3.42^{a}	4.01^{a}
Desamo	1.77^{a}	2.16^{a}	3.59^{a}	4.04^{a}
Year				
2019	1.64^{b}	1.92^{c}	3.37^{b}	4.29^{a}
2020	1.78^{a}	2.38^{a}	3.42^{b}	3.81^{b}
2021	1.82^{a}	2.16^{b}	3.59^{a}	3.93^{b}
Factor interaction				
T	***	ns	****	***
C	ns	ns	ns	ns
Y	***	***	***	***
T × C	*	ns	ns	ns
T ×Y	***	ns	ns	***
C ×Y	***	***	*	ns
T ×C ×Y	ns	ns	ns	***

Explanations as in Table 4.

(Table 9). Slightly larger differences in the trait in question were found between the years. At flowering, the significantly highest LAI was found in the first year of the study.

Significantly higher grain yields were obtained from the treatment with ploughing. The yields from the treatment with reduced tillage (SD) consisting of shallow tillage with a disc harrow were 0.47 t ha^{-1} lower, while the yields from the strip-tillage (ST) treatment were 0.72 t ha^{-1} lower (Table 10). No significant differences in the yield were found between the reduced tillage (SD) and strip-tillage (ST) treatments. Desamo was a significantly lower yielding cultivar. Large differences in yield levels were found between the years. All the cultivars tested showed a higher grain yield with plough tillage, while the differences in the yield, compared to the other treatments, were not significant (Fig. 4). The tillage used in each year of the study differentiated the yield (Fig. 5). In 2019, a significantly higher grain yield was found in the variant with pre-applied ploughing relative to reduced tillage (SD) and strip-tillage (ST). In 2020, pre-applied tillage did not significantly differentiate the grain yield, but in that year of the study, strip-tillage (ST) showed a slightly higher yield relative to reduced tillage (SD), compared to the other years of the study. There were no significant differences in the yield between the cultivars in 2019 (Fig. 6). In 2020, the Formacja cultivar was found to show a significantly higher yield relative to the Metronom and Desamo cultivars, while in 2021, the Desamo cultivar showed a significantly lower yield than the other cultivars.

4. DISCUSSION

The present research confirmed that suitable conditions for plant growth can be achieved with different tillage methods. The differences between the treatments in terms of tillage intensity were relatively large, yet their role in shaping the photosynthetic activity of the wheat plants was relatively small. This indicates that the plant growth conditions did not change significantly according to the tillage method. In the literature, papers can be found in which the tillage method was the cause of very negative changes in plant physiological parameters. Kang *et al.* (2023) explains the negative changes in photosynthetic intensity, stomatal conductance, and transpiration rate by soil water deficiency, which can be caused by improper tillage. The relatively highest values of net photosynthetic intensity in ploughed treatments can be linked to better soil aeration,

Table 10. Grain yield (t ha^{-1}) of winter wheat according to cropping system, cultivar and years of study

Specification	Yield
Cultivation system	
Ploughed tillage + strip-tillage (PT)	7.88^{a}
Stubble discing + strip-tillage (SD)	7.41^{b}
Strip-tillage (ST)	7.16^{b}
Cultivar	
Formacja	7.68^{a}
Metronom	7.53^{a}
Desamo	7.24^{b}
Year	
2019	8.10^{a}
2020	7.73^{b}
2021	6.62^{c}
Factor interaction	
T	***
C	***
Y	***
T × C	ns
T ×Y	ns
C ×Y	***
T ×C ×Y	ns

Explanations as in Table 4.

and therefore, to more intensive organic matter mineralisation processes and higher nitrogen availability, as pointed out by Noor *et al.* (2021, 2023).

The intensity of photosynthetic processes is also influenced by genetic factors, as shown by Bishop and Bugbee (1998) and Jobson *et al.* (2019), Wang *et al.* (2016), Agisho and Hairat (2021), and Tumebo (2021). The physiological parameters of individual cultivars influence their response to stress conditions, whose severity varies from year to year and depends primarily on weather conditions (Buczek *et al.*, 2021). In our study, the role of weather conditions in shaping plant physiological parameters was very high, but did not depend significantly on the cultivar, as in the study conducted by Fang *et al.* (2023). This was probably related to the fact that the cultivars included in the study were registered in Poland, which necessarily implied their similarly high suitability for cultivation in the climatic conditions of this country. The weather conditions varied from year to year when the physiological parameters were measured. The most favourable weather conditions in terms of the amount and distribution of precipitation and in terms of temperature during the period of intensive growth of wheat plants occurred in 2021, and therefore the highest net photosynthesis was recorded in that year. Less favourable weather conditions occurred in 2020, when the precipitation during the period of intensive growth of the wheat plants far exceeded the perennial norms, while at the same time the temperatures were clearly below the perennial norm. Consequently, the level of net photosynthesis intensity was then the lowest, which was influenced by the unfavourable thermal conditions.

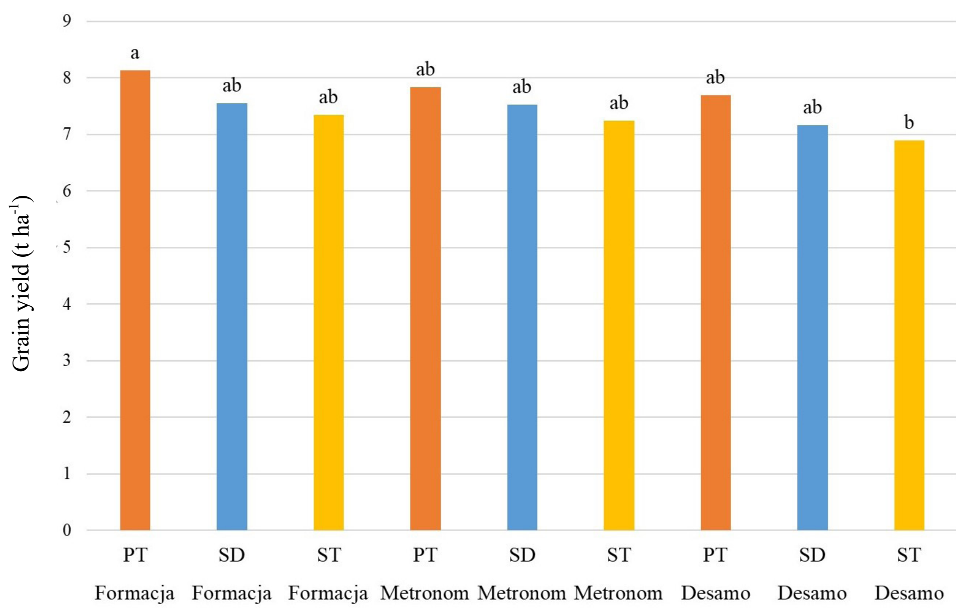


Fig. 4. Effect of tillage and cultivar on winter wheat grain yield (t ha^{-1}). Different letters (a, b) mean significant differences (α = 0.05). The abbreviations: plouged tillage + strip-tillage (PT), stubble discing + strip-tillage (SD), strip-tillage (ST).

Fig. 5. Effect of tillage and years of study: 2019, 2020, 2021 on winter wheat grain yield (t ha^{-1}). Different letters (a-f) mean significant differences (α = 0.05). The abbreviations: plouged tillage + strip-tillage (PT), stubble discing + strip-tillage (SD), strip-tillage (ST).

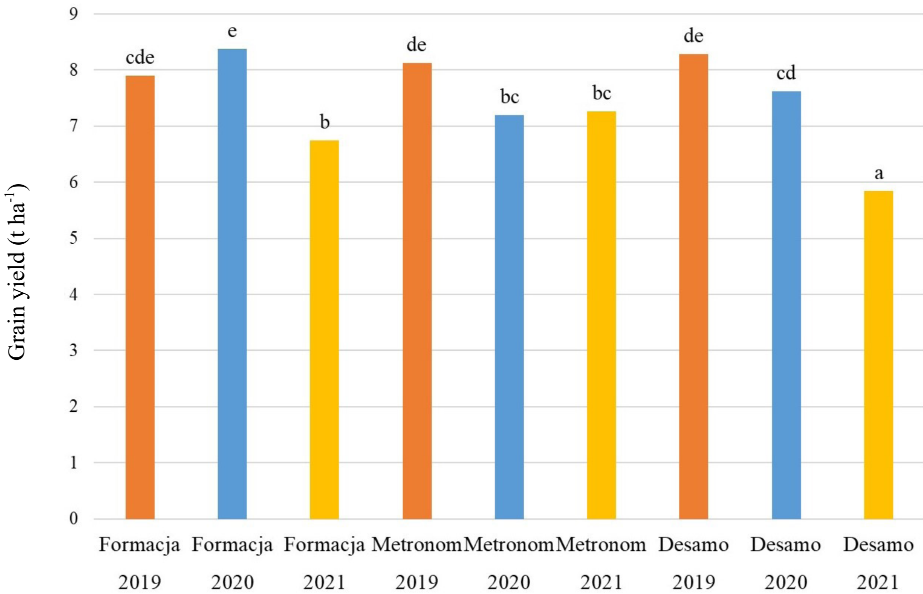


Fig. 6. Effect of cultivar and years of study: 2019, 2020, 2021 on winter wheat grain yield (t ha^{-1}). Different letters (a-e) mean significant differences (α = 0.05).

Tillage simplifications can affect the availability of water to plants in association with reduced water losses (Putra and Yuliando, 2015). Similar conclusions were drawn by van Hateren *et al.* (2021) and Zhao *et al.* (2021), who explained the reduced rainwater losses by improved infiltration into the soil profile. In our study, in each of the treatments differing in the tillage method, the level of the *WUE* index was similarly high, indicating that water availability was similar between the treatments.

The cultivars differed in their water use efficiency (*WUE*), but the differences were not the same between the dates. At the flag leaf and flowering stages, they reached 10%, but no more than 5% after earing. The influence of the genetic factor on *WUE* was also confirmed by other researchers (Buczek *et al.*, 2021). As suggested by Zhang *et al.* (2010), intervarietal differences in *WUE* should be linked to their different drought tolerance. Undoubtedly, the differences in the water use index could be greater if the rainfall deficit stress conditions were greater.

The *WUE* value can also be varied by other agronomic factors. In a study conducted by Latifmanesh *et al.* (2023), the use of maize as a forecrop resulted in higher *WUE* and leaf photosynthetic rates in wheat due to the ability to use water from upper and deeper soil layers at different stages of wheat development. Similarly, Álvaro-Fuentes *et al.* (2009) found that diversifying crop rotations in cereal crops increases *WUE*. In the present study, the species under study were always sown in the same rotation (after wheat was sown after oilseed rape); therefore, this was the factor which diversified *WUE*.

The presence of crop residues on the soil surface is very important for changes in water loss. A study conducted by Zhang *et al.* (2017) showed that mulch on the soil surface increased *WUE* by 61%. This was related to the fact that the soil surface was better protected from excessive evaporation. A similarly large increase in *WUE* due to mulch application was found by Ali *et al.* (2018a). In our study, the differences were not that big. Greater differences were found in the years of the study. Water content in the soil is closely related to precipitation and its loss due to evapotranspiration. The lower rainfall and the higher temperature during the period of photosynthesis measurements (in May and June) resulted in a larger negative value of the climatic water balance in 2019, *i.e.* it amounted to -287, which resulted in a lower *WUE* value than in the other two years. In the experimental set-up used, the differences in the degree of soil surface coverage were very large. With plough tillage, there was no such residue on the soil surface at all, in contrast to reduced tillage (SD) and strip-tillage (ST), in which the soil cover of shredded crop residues reached several percent. Therefore, the greatest rainwater losses were recorded in the ploughed treatment. However, they were not large enough to affect the growth parameters of the plants and the associated *WUE*.

The leaf cover index LAI is an indicator of the spatial structure of a plant canopy expressed by the density of leaves per unit area and indirectly a determinant of the course of plant development processes (Czerednik and Nalborczyk, 2000; Kałuża and Strzeliński, 2009). It expresses the ratio of the assimilative area of leaves capable of absorbing PAR, on which photosynthesis depends, to the ground surface. Its measurement at particular phases of plant development makes it possible to estimate the dynamics of growth and vegetative biomass accumulation affecting subsequent yield (Czerednik and Nalborczyk, 2000; Glenn *et al.*, 2008). The relationship between vegetative biomass building and subsequent yield is being considered in breeding programmes of new winter wheat cultivars, so it is important to evaluate this parameter objectively (Bellundagi *et al.*, 2013; Jańczak-Pieniążek *et al.*, 2022; Kaya, 2022). Studies reported by Jaskulska and Jaskulski (2021) and Jańczak-Pieniążek *et al.* (2022) showed that ploughing can positively affect LAI values. Our study confirmed this, as a higher LAI value was obtained in the PT tillage system compared to SD and ST. However, no significant effect of the cultivar on the LAI value was shown. Studies conducted by other authors generally show significant intervarietal differences for this trait (Tian *et al.*, 2011; Rachoń and Szumiło, 2015; Rachoń *et al.*, 2018). Oleksy *et al.* (2009) studied seven cultivars of winter wheat and showed that the LAI value at the earing stage was in the range from 3.62 to 3.84, while the value in the present study was higher in all the cultivars tested. As with the physiological parameters, the LAI parameter was also strongly influenced by the weather conditions varying over the years, as also pointed out by other authors (Rachoń *et al.*, 2018; Wang *et al.*, 2022; Zhuo *et al.*, 2022).

Grain yield is the result of correct agrotechnology and the selection of an appropriate cultivar. Suitable growth conditions for a given cultivar determine the intensity of photosynthesis in wheat plants and, as a result, also the yield (Wafae *et al.*, 2023). In the current study, the highest *Pn* index was found in the plough tillage, from which the highest grain yields were achieved. A strong relationship between the magnitude of the *Pn* coefficient and yield was pointed out by Feng *et al.* (2014), who further noted that its magnitude depends on the cultivar, but can also be shaped by agrotechnical treatments. Similar results were also obtained by Driever *et al.* (2017).

Some authors point out that, in simplified cultivation conditions, winter wheat yield decreases due to increased intensity of fungal diseases (Parylak and Pytlarz, 2013). In our study, this was not confirmed, *i.e.* the level of infestation of the wheat plants by various diseases was similar. Perhaps this was determined by the relatively good position in the crop rotation (second year after winter oilseed rape). This fact determined the generally low pressure of diseases - the same in all treatments. A similar direction of changes in the yield of wheat grown in simplified cultivation conditions was obtained by Jaskulska *et al.* (2013) and Saldukaitė-Sribikė *et al.* (2022). In the case of no-till farming, it is possible to breed cultivars with specific adaptations to conservation agriculture, although the genetic control of adaptation appears to be very complex and is strongly influenced by the environment, soil type, planting method, and crop rotation (Trethowan *et al.,* 2012). As shown by Kotwica *et al.* (2014), in the cultivation of wheat after wheat, the yield is more beneficially influenced by ploughing in crop residues during seeding cultivation or by simultaneously using the removal of crop residues and effective microorganisms that support its decomposition. The present study also showed a better effect of the pre-sowing plough cultivation, and the lack of significant differences in the grain yield between the reduced (SD) and strip-tillage (ST) could be due to the removal of straw from the arable strips.

5. CONCLUSIONS

The tillage method significantly affected photosynthesis intensity. It was the highest in the treatment where ploughing was applied and from which the highest wheat yield was obtained. The highest stomatal conductance was also recorded in this treatment. The role of tillage in shaping the intracellular CO_2 concentrations was significantly lower.

The effect of the soil cultivation method and the cultivar on water use efficiency was small, although it should be noted that periodically (beginning of earing) stubble discing + strip-tillage (stubble discing) had a positive effect on this index.

The benefits of not using plough cultivation with a relatively small reduction in yield, compared to reduced tillage and strip-tillage, show that the lack of ploughing does not have large negative consequences on the yield while reducing time, fuel consumption, and carbon dioxide emissions. Not using minimum tillage seems to be justified by the lack of a significantly lower yield compared to using only the strip-tillage method.

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