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Spring barley response to tillage systems and crop residues

Reakcja jęczmienia jarego na systemy uprawy roli i resztki pożniwne

Summary. The present study aimed to assess the effect of tillage systems and crop residues on grain yield and weed infestation of spring barley. The experiment was established with the method of randomized sub-blocks. The main experimental factor was the tillage system (TS): conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). The second experimental factor included plots with crop residues (CR): straw (S) or without straw (WS). A higher grain yield of barley was determined in the RT than NT system. The RT system allowed producing a higher spike number and a higher 1000 grain weight. A higher grain yield was also obtained on the plots with straw (S) than without straw (WS). Greater weed density in barley stands was determined on RT and NT plots without crop residues (WS), whereas the lowest one was found on the CT plots with the residues (S). The air-dry weight of weeds was higher on the NT plots without crop residues (WS) than on the other plots, while the lowest air-dry weight of weeds was determined on the CT plots with the residues (S). The biodiversity of weeds in a barley stand was greater on the WS than on the S plots.

Key words: tillage system, crop residues, grain yield, weed infestation, Shannon-Wiener's diversity index

INTRODUCTION

The task of tillage is to create optimal conditions for plant growth and yielding. On moderately moist soil, this task can be accomplished by cultivation using a mouldboard plough, whereas on soils with water shortages – using a seeder for no-till sowing

[Gruber et al. 2012]. In the conventional system, the main tillage is performed with the mouldboard plough, while measures deployed after plowing include harrowing, cultivating, sometimes rolling or subsoiling, depending on soil condition. In the no-tillage system, only glyphosate-containing herbicides are applied between previous crop harvest and succeeding crop sowing instead of the mechanical tillage [Derpsch et al. 2010, Koning et al. 2019]. Preparation of soil for sowing and the sowing of seeds are most often performed in the stubble with one pass of the machine for no-till sowing. In turn, surface-operating tools are recommended in the reduced tillage system [Morris et al. 2010, Aziz et al. 2013, Dębska et al. 2020], whereas leaving crop residues onto field surface was found to be the optimal tillage variant on the plots exposed to erosion [Döring et al. 2005]. According to Morris et al. [2010], the coverage of a field surface with crop residues should account for at least 30% or 1120 kg of the weight of the left residues. Another task of leaving crop residues on a field surface is to enrich the soil in organic matter, which promotes its biological and enzymatic activity, increases organic carbon content, and improves its structure and water absorption capacity [Li et al. 2014]. Also Wang et al. [2019] reported that field amendment with crop residues provided soil with many benefits by reducing evaporation, increasing microbial biomass, maintaining soil organic carbon balance, increasing nutrient cycling, promoting soil enzyme activity, and increasing soil aggregate stability. Crop residues were also reported to suppress weeds, provide a suitable habitat for beneficial insects, and act as non-host plants for nematodes and other pests in crop rotation [Lu et al. 2000]. Leaving them on the field is of great importance at farms where animal husbandry has been limited or abandoned.

Opinions on plant yield in the conventional and no-tillage systems are inexplicit and depend on habitat-related factors, soil quality, and the level of agro-engineering measures [Zikeli et al. 2013, Jaskulska et al. 2018, Woźniak 2019]. The no-tillage system is often used by farmers because it reduces production costs compared to the conventional cultivation [Haliniarz et al. 2018]. Nevertheless, as reported by De Vita et al. [2007], strong correlations can be noticed between wheat grain yield, tillage system, and the sum of precipitation in the growing season. The no-tillage system promotes cereal yields in periods of low precipitation, while the conventional tillage system – when the sum of precipitation is high. The better production effect in the NT system is due to lesser water evaporation from the soil, which results in its greater availability to plants [De Vita et al. 2007]. Also Ruisi et al. [2014] showed that the no-tillage system ensured a higher wheat grain yield at reduced precipitation, whereas the conventional tillage system increased grain yield under conditions of optimal water availability. In the experiment performed by Woźniak and Kwiatkowski [2013] on moderately moist soil, a higher barley grain yield was achieved in the conventional than in the reduced and herbicide tillage systems. The tillage system was also reported to affect wheat grain quality. López-Bellido et al. [2001] demonstrated a more beneficial effect of conventional than no-tillage system on grain quality and claimed this was due to better nitrogen availability to plants. Also Ruisi et al. [2014] showed that the conventional tillage system increased the protein content of wheat grain, compared to the no-tillage system.

The tillage systems were also reported to influence the condition and structure of crop infestation by weeds [Woźniak 2018]. Unlike to conventional tillage, the no-tillage system facilitates an increase in weed number and weight [Gruber et al. 2012]. In addition, it influences the species composition of weeds and their distribution in the crop stand. Research by Woźniak [2018] showed a higher number of weed species belonging to the upper and medium level of the wheat crop stand in the no-tillage than in the conventional system. These weeds are taller or similar in height to cereals (common windgrass, poppy seeds, common wild oat), they ripen before their harvest, and spread easily with wind or during harvest. As reported by Hernández Plaza et al. [2015], the tillage system also affects weed seed distribution in the soil. The NT system promotes species with fine seeds of high fertility, capable to germinate from soil surface. In turn, crop stands in the conventional tillage are predominated by large-seeded weed species able to germinate from deeper soil layers. These observations underly the weed control strategy in crop stands.

The cited literature and previous research enable formulating a hypothesis assuming that on moderately humid areas, a higher spring barley grain yield can be achieved in the CT system than in the RT and NT systems. Also leaving crop residues on field surface may effectively reduce weed density, thereby enhancing grain yield. The present study aimed to assess the effect of tillage systems and crop residues (straw) on grain yield and weed infestation of spring barley.

MATERIALS AND METHODS

Experiment location and soil and weather conditions

A field experiment was conducted in the years 2018–2020 at the Uhrusk Experimental Farm, belonging to the University of Life Sciences in Lublin (south-eastern Poland, 51°18'N, 23°36'E). The soil at the farm was classified as Rendzic Phaeozem [IUSS Working Group WRB 2015], with the composition of sandy loam, alkaline pH, high contents of phosphorus and potassium, and medium contents of magnesium, mineral nitrogen, and organic carbon (Tab. 1).

Table 1. Physicochemical properties of soil (in 0–25 cm layer)

Specification	Value
Clay: <0.002 mm (%)	22.0
Silt: 0.002–0.05 mm (%)	25.0
Sand: 0.05–2.0 mm (%)	53.0
Organic C (g kg^{-1})	11.7
Total N (g kg^{-1})	0.69
Available P (mg kg^{-1})	130.0
Available K (mg kg^{-1})	220.0
Available Mg (mg kg^{-1})	70.0
pH_{KCl}	7.1

The growing season (i.e., the number of days with the mean air temperature above +5°C) began in the third week of March and lasted 210–215 days. In the spring and summer months (May–October), the sum of precipitation ranged from 269 mm (2018) to 358 mm (2020), whereas in the autumn and winter months (November–April), it ranged from 129 mm (2019) to 142 mm (2018). The highest air temperatures were recorded in June, July, and August (from 19°C to 21°C on average), whereas the lowest ones – in January and February (from –4.3°C to 1.6°C) – Figure 1.

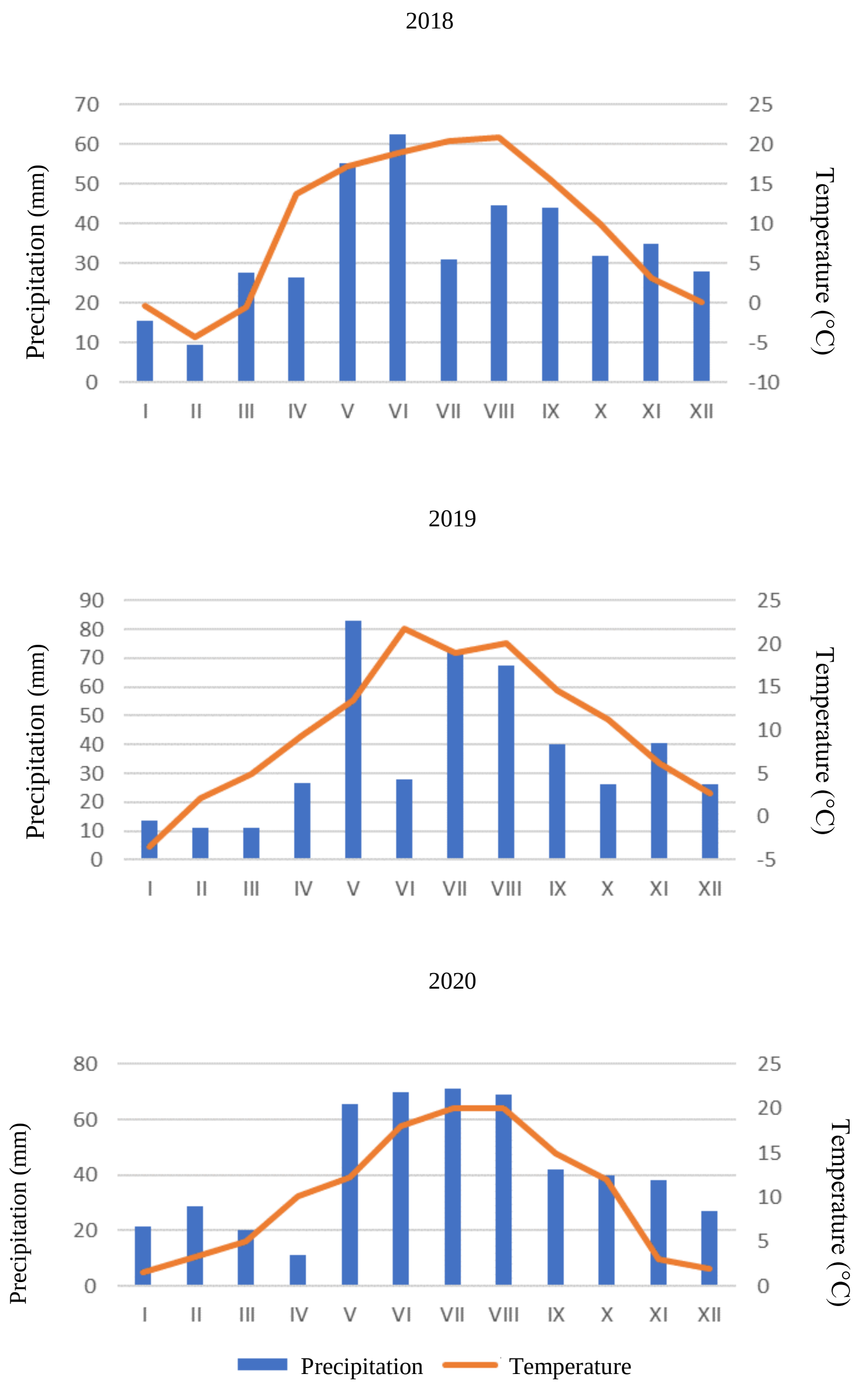

Figure 1. Average monthly temperature and precipitation

Experimental scheme

The experiment was established in the system of randomized sub-blocks (6 m × 25 m) in three replications. The main experimental factor was the tillage system (TS): (1) conventional tillage (CT), (2) reduced tillage (RT), and (3) no-tillage (NT). The second experimental factor included plots with crop residues (CR): (i) straw (S) or (ii) without straw (WS). Spring barley was cultivated in the following crop rotation: peas – durum wheat – spring barley. Crop residues included cut straw left on the field after durum wheat harvest. On CT plots, the crops residues were mixed with soil during shallow ploughing, on RT plots – they were mixed with soil during field cultivation, whereas on NT plots – they remained on field surface until spring barley sowing. The weight of crop residues was 3.6 t ha^{-1} (2018 and 2019) and 3.9 t ha^{-1} (2020).

Soil cultivation, sowing, fertilization, and plant protection

In the CT system, shallow ploughing with harrowing was performed after previous crop harvest, and pre-winter ploughing in the autumn (Tab. 2). In the RT system, soil was double-cultivated, whereas only a glyphosate-containing herbicide was applied in the NT system. A cultivation unit composed of a cultivator, a string roller, and a harrow was used on all plots in the spring time.

Table 2. Scheme of soil tillage for spring barley cultivation

Tillage system	Cultivation measures		
	post-harvest	pre-winter	spring
CT[a]	shallow ploughing (at a depth of 10 cm) + harrowing	pre-winter ploughing (at a depth of 25 cm)	cultivation unit
RT	cultivation (double)	lack	
NT	glyphosate (4 dm^3 ha^{-1} a.s. 360 g dm^{-3})		

CT[a] – conventional tillage, RT – reduced tillage, NT – no-tillage.

Spring barley of 'Tocada' cultivar was sown in the first week of April, at sowing density of 320 seeds m^{-2}. Mineral fertilization was as follows: 90 kg N ha^{-1}, 30 kg P ha^{-1}, and 80 kg K ha^{-1}. Nitrogen was administered in three doses: 50 kg ha^{-1} before sowing, 20 kg ha^{-1} at the shooting stage (33–34 stage in the BBCH scale – Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) [Meier 2001], and 20 kg ha^{-1} at the ear formation stage (53–54 BBCH). In turn, phosphorus and potassium fertilizers were applied in single doses before sowing. Barley crop protection from weeds involved stand harrowing at the tillering stage (23–24 BBCH), whereas the protection against fungal diseases was ensured by fungicides containing flusilazole + carbendazime applied at the shooting stage (33–34 BBCH) and propiconazole + fenpropidin applied at the ear formation stage (53–54 BBCH).

Production traits and statistical analysis

Analyses were conducted to evaluate spring barley grain yield and its components (spike number per 1 m^2, grain mass per spike, and 1000 grain weight) as well as weed infestation in three terms: T_1 – in the autumn, 40 days after the previous crop harvest; T_2 – in the spring, at the barley tillering stage (21–22 BBCH), and T_3 – in the summer, before barley harvest (81–82 BBCH). The evaluation of weed infestation in T_1, T_2, and T_3 involved determining the species composition of weeds and weed number per 1 m^2, and additionally air-dry weight of weeds in T_3. The weed number, weed species composition, and air-dry weight of weeds were evaluated twice on the 1 m^2 area randomly selected from each plot. The determination of the air-dry weight of weeds consisted in collecting weeds from the specified areas, removing their root system, and placing their aerial parts in a well-ventilated room on an openwork shelf. In addition, values of the Shannon-Wiener's diversity index (*H'*) were computed using the following formula:

$$H' = -\sum\left(\frac{ni}{N}\right)\log\left(\frac{ni}{N}\right)$$

where: *ni* – number of individuals of each species; *N* – total number of individuals of all species.

Results obtained were developed statistically using the analysis of variance (ANOVA), whereas the significance of differences between mean values was determined with the Tukey's HSD test, $p < 0.05$.

RESULTS

Grain yield and its components

A higher grain yield of spring barley was determined on RT than NT plots (Tab. 3). The RT system also allowed producing a higher spike number per 1 m^2 and a higher 1000 grain weight. A higher grain yield was also obtained on the plots with post-harvest residues (S) than on those without the residues (WS). In addition, the S plots produced a higher barley spike number per 1 m^2 and a higher 1000 grain weight than the WS plots. A higher grain yield was also determined in 2020 than in 2018 and 2019, which was mainly due to a higher spike number m^{-2}. Grain yield was also affected by TS × CR and TS × Y interactions, with the highest grain yield obtained from RT plots with crop residues (S) and in 2020 compared to 2018 and 2019.

Number and air-dry weight of weeds

In the autumn (term T_1), greater weed density per 1 m^2 was observed on RT plots, smaller one on CT plots, and the smallest one on NT plots (Tab. 4). In addition, a 3-fold higher weed number per 1 m^2 was determined on the WS plots than on the S plots. Weed density was also affected by TS × CR interaction. The highest weed number was determined on RT plots without straw (WS), whereas the lowest one – on the NT plots with the residues (S).

At the stage of spring barley tillering (term T_2), a higher weed number per 1 m^2 was found on RT and NT plots than on CT plots. A significantly greater weed density was also determined on the WS than S plots well as in 2018 than in 2019 and 2020. Weed density was additionally affected by TS × CR and TS × Y interactions. A higher number of weeds per 1 m^2 was determined on RT and NT plots without crop residues (WS), whereas the lowest one was found on the CT plots with the residues (S). In addition, a higher weed number was determined on RT and NT plots in 2018 compared to the other years tested.

Table 3. Grain yield of spring barley and its components

Specification	Grain yield (t ha^{-1})	Spike number (m^{-2})	Grain weight per spike (g)	1000 grain weight (g)
tillage system (TS)				
CT	$6.81^{a.b}$	550^{a}	1.24^{a}	46.7^{a}
RT	6.92^{a}	556^{a}	1.26^{a}	47.0^{a}
NT	6.71^{b}	530^{b}	1.27^{a}	45.8^{b}
Mean	6.81	545	1.25	46.5
crop residue (CR)				
S	7.01^{a}	567^{a}	1.24^{a}	47.5^{a}
WS	6.62^{b}	522^{b}	1.27^{a}	45.4^{b}
Mean	6.81	545	1.25	46.5
years (Y)				
2018	6.72^{b}	$543^{a.b}$	1.23^{b}	$46.7^{a.b}$
2019	6.75^{b}	522^{b}	1.29^{a}	47.3^{a}
2020	6.97^{a}	570^{a}	1.22^{b}	45.6^{b}
Mean	6.81	545	1.25	46.5
ANOVA				
TS	*	*	ns	*
CR	*	**	ns	**
Y	*	*	*	*
TS × CR	**	ns	ns	*
TS × Y	*	*	ns	ns
CR × Y	ns	*	ns	ns
TS × CR × Y	*	ns	ns	*

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters indicate significant differences. Significant effects: $p < 0.05$ (*), $p < 0.01$ (**), ns – not significant.

Before barley harvest (term T_3), the highest weed number per 1 m^2 was recorded in RT and NT systems than in the CT system, and also on WS than S plots. Weed density was additionally affected by TS × CR interaction. A higher number of weeds per 1 m^2 was determined on RT and NT plots without crop residues (WS), whereas the lowest one – on the CT plots with the residues (S). In this analytical term, analyses were also conducted to determine the air-dry weight of weeds (Tab. 5). It was significantly higher on NT than CT plots as well as on WS than S plots. The air-dry weight of weeds was additionally affected by TS x CR interaction. The weeds produced greater biomass in the NT system without crop residues (WS), while the lowest one in the CT system with crop residues (S).

Table 4. Weed number per 1 m^2 depending on evaluation term: T_1 – 40 days after the previous crop harvest; T_2 – in the springtime, at the tillering stage of spring barley (21–22 BBCH); T_3 – before spring barley harvest (81–82 BBCH)

Specification	T_1	T_2	T_3
tillage system (TS)			
CT	12.7^b	11.3^b	8.1^b
RT	18.8^a	20.1^a	14.7^a
NT	6.6^c	19.3^a	12.4^a
Mean	12.7	16.9	11.7
crop residue (CR)			
S	6.2^a	12.7^b	8.9^b
WS	19.1^b	21.1^a	14.5^a
Mean	12.7	16.9	11.7
years (Y)			
2018	13.7^a	27.3^a	13.7^a
2019	12.4^a	14.3^b	9.0^a
2020	11.9^a	9.1^b	12.6^a
Mean	12.7	16.9	11.7
ANOVA			
TS	*	*	*
CR	**	**	*
Y	ns	*	ns
TS × CR	*	*	*
TS × Y	ns	*	ns
CR × Y	ns	ns	ns
TS × CR × Y	ns	*	ns

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters indicate significant differences. Significant effects: $p < 0.05$ (*), $p < 0.01$ (**), ns – not significant.

Table 5. Air-dry weight of weeds (g m^{-2}) in term T_3

Specification	T_3
tillage system (TS)	
CT	13.4[b]
RT	21.9[a.b]
NT	28.2[a]
Mean	21.2
crop residue (CR)	
S	12.1[b]
WS	30.2[a]
Mean	21.2
years (Y)	
2018	18.9[a]
2019	23.9[a]
2020	20.7[a]
Mean	21.2
ANOVA	
TS	**
CR	**
Y	ns
TS × CR	*
TS × Y	ns
CR × Y	ns
TS × CR × Y	ns

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters indicate significant differences. Significant effects: $p < 0.05$ (*), $p < 0.01$ (**), ns – not significant.

Species composition of weeds

The tillage system and crop residues differentiated the species composition of weeds. In term T_1, all plots were mostly populated by short-lasting spring and winter weeds (Tab. 6). In the CT system, the S plots were infested by 5–6 species, the prevailing of which included: *Amaranthus retroflexus*, *Avena fatua*, *Apera spica-venti*, *Galium aparine*, and *Echinochloa crus-galli*; whereas the weeds identified on WS plots included 5–8 species, the predominating of which included: *A. spica-venti*, *A. retroflexus*, *A. fatua*, *E. crus-galli*, *Setaria pumila*, *G. aparine*, and *Veronica persica*. In the RT system, 4–8 species were identified in the weed community found on the S plots, including mainly: *A. spica-venti*, *A. fatua*, *A. retroflexus*, *G. aparine*, and *S. pumila*; whereas the WS plots were populated by 6–8 species, with the greatest density observed for: *A. retroflexus*, *A. spica-venti*, *S. pumila*, *E. crus-galli*, *A. fatua*, *G. aparine*, *Papaver rhoeas*, and *Lamium purpureum*. In the NT system, the weed community found on the S plots was composed of 2–4 species, the prevailing of which included: *E. crus-galli*, *S. pumila*, *A. retroflexus*, and *Thlaspi arvense*; whereas the WS plots were infested by 4–5 weed species, including mainly: *A. retroflexus*, *E. crus-galli*, *S. pumila*, *T. arvense*, and *P. rhoeas*.

Table 6. Species composition of weeds in term T_1 (40 days after the previous crop harvest)

Species composition	CT		RT		NT	
	S	WS	S	WS	S	WS
2018						
Amaranthus retroflexus L.	2.8^{c}	4.2^{b}	0.8^{d}	8.6^{a}	–	$3.2^{b.c}$
Apera spica-venti (L.) P. Beauv.	3.2^{b}	5.4^{a}	2.2^{b}	6.4^{a}	–	1.2^{c}
Galeopsis tetrahit L.	–	0.8^{a}	–	0.2^{a}	–	–
Lamium purpureum L.	0.2^{b}	1.2^{a}	–	0.2^{b}	0.2^{b}	–
Papaver rhoeas L.	–	0.2^{b}	0.8^{b}	4.2^{a}	–	–
Setaria pumila (Poir.) Roem & Schult.	1.0^{b}	3.3^{a}	–	–	0.8^{b}	2.8^{a}
Echionochloa crus-galli (L.) P.Beauv.	1.8^{c}	4.2^{b}	–	6.5^{a}	1.8^{c}	4.2^{b}
Thlapsi arvense L.	0.8^{b}	–	0.8^{b}	2.8^{a}	–	0.8^{b}
Viola arvensis Murray	–	0.8^{b}	0.2^{b}	3.2^{a}	0.2^{b}	–
Number of weeds per 1 m^2	9.8^{c}	20.1^{b}	4.8^{d}	32.1^{a}	3.0^{d}	12.2^{c}
Number of species	6	8	5	8	4	5
2019						
Amaranthus retroflexus L.	5.2^{b}	3.8^{c}	2.4^{c}	10.5^{a}	0.8^{d}	7.2^{b}
Avena fatua L.	2.2^{b}	4.0^{a}	3.0^{b}	3.8^{a}	–	3.2^{b}
Erigeron canadensis L.	0.2^{b}	0.2^{b}	–	2.2^{a}	–	–
Galium aparine L.	3.2^{a}	3.9^{a}	–	3.4^{a}	–	0.8^{b}
Papaver rhoeas L.	0.8^{b}	1.8^{b}	1.2^{b}	3.2^{a}	1.2^{b}	2.8^{a}
Setaria pumila (Poir.) Roem & Schult.	–	–	0.2^{b}	3.2^{a}	–	–
Number of weeds per 1 m^2	11.6^{b}	13.9^{b}	6.8^{c}	26.3^{a}	2.0^{d}	14.0^{b}
Number of species	5	5	4	6	2	4
2020						
Amaranthus retroflexus L.	3.6^{b}	$4.2^{a.b}$	1.8^{c}	5.2^{a}	0.2^{d}	3.6^{b}
Avena fatua L.	2.2^{b}	2.8^{b}	2.6^{b}	4.8^{a}	–	0.5^{c}
Lamium purpureum L.	–	0.2^{b}	0.2^{b}	5.8^{a}	–	–
Papaver rhoeas L.	0.8^{b}	1.0^{b}	0.8^{b}	5.0^{b}	0.2^{c}	0.8^{b}
Setaria pumila (Poir.) Roem & Schult.	–	–	1.6^{b}	4.3^{a}	–	0.2^{c}
Sonchus oleraceus L.	–	1.2^{b}	0.2^{c}	2.2^{a}	–	–
Thlapsi arvense L.	0.8^{b}	–	0.8^{b}	1.8^{a}	0.8^{b}	1.8^{a}
Veronica persica Poir.	0.2^{c}	3.8^{a}	1.2^{b}	4.2^{a}	–	–
Number of weeds per 1 m^2	7.6^{c}	13.2^{b}	9.2^{c}	33.3^{a}	1.2^{d}	6.9^{c}
Number of species	5	6	8	8	3	5

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters in line significant differences, $p < 0.05$.

Table 7. Species composition of weeds at the tillering stage of spring barley (T_2)

Species composition/ Years	CT		RT		NT	
	S	WS	S	WS	S	WS
2018						
Apera spica-venti (L.) P. Beauv.	1.8^{d}	4.3^{c}	4.0^{c}	6.5^{b}	6.0^{b}	9.8^{a}
Avena fatua L.	$5.2^{b.c}$	7.0^{b}	6.2^{b}	10.5^{a}	4.8^{c}	7.6^{b}
Fallopia convolvulus (L.) A. Löve	1.0^{d}	3.4^{c}	8.3^{a}	8.9^{a}	5.2^{b}	$4.6^{b.c}$
Galeopsis tetrahit L.	–	2.2^{b}	1.8^{b}	4.2^{a}	–	4.0^{a}
Galium aparine L.	2.2^{b}	2.9^{b}	6.6^{a}	7.9^{a}	2.5^{b}	3.8^{b}
Papaver rhoeas L.	0.2^{d}	$2.2^{b.c}$	0.8^{d}	1.8^{c}	2.6^{b}	4.2^{a}
Stellaria media (L.) Vill.	–	0.6^{b}	–	1.8^{a}	2.0^{a}	–
Tripleurospermum indorum (L.) Sch. Bip.	–	0.2^{b}	–	2.0^{a}	–	–
Viola arvensis Murray		1.2^{a}			0.8^{a}	
Number of weeds per 1 m^2	10.4^{d}	24.0^{c}	27.7^{c}	43.6^{a}	23.9^{c}	34.0^{b}
Number of species	5	9	6	8	7	6
2019						
Anthemis arvensis L.	–	2.5^{a}	–	1.9^{a}	0.8^{b}	1.9^{a}
Apera spica-venti (L.) P. Beauv.	0.8^{d}	$1.0^{c.d}$	1.8^{c}	4.3^{b}	6.0^{b}	9.0^{a}
Avena fatua L.	3.4^{b}	4.9^{a}	0.2	2.5^{b}	3.0^{b}	3.2^{b}
Cirsium arvense L. Scop.	–	–	–	0.8	–	–
Consolida regalis Gray	–	0.8^{b}	1.8^{a}	–	–	1.8^{a}
Fallopia convolvulus (L.) A. Löve	0.8^{c}	–	2.2^{b}	3.2^{a}	2.0^{b}	–
Galeopsis tetrahit L.	–	1.2^{a}	–	1.8^{a}	–	1.6^{a}
Papaver rhoeas L.	1.0^{c}	1.8^{b}	2.2^{b}	0.8	4.3^{a}	1.8^{b}
Sonchus oleraceus L.	–	–	–	3.3^{b}	–	5.5^{a}
Number of weeds per 1 m^2	6.0^{d}	12.2^{c}	8.2^{d}	18.6^{b}	16.1^{b}	24.8^{a}
Number of species	4	6	6	8	5	7
2020						
Avena fatua L.	–	8.1^{a}	7.6^{a}	9.0^{a}	4.5^{b}	3.8^{b}
Elymus repens (L.) Gould	–	–	0.2^{a}	0.8^{a}	–	–
Fallopia convolvulus (L.) A. Löve	–	1.8^{a}	–	–	2.0^{a}	–
Galium aparine L.	1.2^{c}	1.8^{b}	–	$2.4^{a.b}$	3.0^{a}	1.8^{b}
Lamium purpureum L.	–	0.4^{a}	0.6^{a}	–	–	0.2^{a}
Papaver rhoeas L.	1.0^{a}	–	–	1.6^{a}	2.0^{a}	–
Sonchus oleraceus L.	–	0.8^{a}	–	0.2^{a}	–	–
Number of weeds per 1 m^2	2.2^{b}	12.9^{a}	8.4	14.0^{a}	11.5^{a}	5.8^{b}
Number of species	2	5	3	5	4	3

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters in line significant differences, $p < 0.05$.

Before barley harvest (term T_3), the weed community developed on CT plots with crop residues (S) included 3–4 species (Tab. 8), the prevailing of which included: *A. fatua*, *G. aparine*, and *P. rhoeas*; whereas that found on WS plots included 4–5 species, the most abundant of which were: *A. fatua*, *P. rhoeas*, *G. aparine*, and *F. convolvulus*. In the RT system, the S plots were infested by 4–5 weed species, including mainly: *A. fatua*, *P. rhoeas*, *G. aparine*, and *F. convolvulus*; whereas the WS plots – by 5–7 species, including mainly: *A. fatua*, *G. aparine*, and *P. rhoeas*. In the NT system, 3 to 5 weed species were identified on the plots with crop residues (S), including mainly: *A. fatua, P. rhoeas,* and *F. convolvulus*; whereas 4 to 7 species on the WS plots, including mainly: *A. fatua*, *P. rhoeas*, *G. aparine*, and *F. convolvulus.* Also other species, including *Sonchus oleraceus*, *Tripleurospermum inodorum*, *Viola arvensis*, and *Stellaria media* were relatively abundant in various study years.

Table 8. Species composition of weeds before spring barley harvest (T_3)

Species composition	CT		RT		NT	
	S	WS	S	WS	S	WS
2018						
Avena fatua L.	4.2^{c}	6.3^{b}	7.8^{a}	9.3^{a}	4.8^{c}	9.0^{a}
Elymus repens (L.) Gould	–	0.5^{b}	–	1.8^{a}	–	–
Galeopsis tetrahit L.	–	–	0.6^{a}	0.8^{a}	–	0.4
Galium aparine L.	1.2^{c}	2.4^{b}	4.0^{a}	4.4^{a}	0.8^{c}	2.8b
Papaver rhoeas L.	–	1.2^{b}	2.0^{a}	$1.8^{a.b}$	–	2.2^{a}
Setaria pumila (Poir.) Roem & Schult.	0.2^{b}	–	–	0.8^{a}	0.2^{b}	1.4^{a}
Sonchus oleraceus L.	0.8^{b}	$1.2^{a.b}$	–	–	1.6^{a}	2.2^{a}
Tripleurospermum indorum (L.) Sch. Bip.	–	–	1.8^{b}	2.8^{a}	–	0.8^{b}
Number of weeds per 1 m^2	6.4^{d}	11.6^{c}	16.2^{b}	21.7^{a}	7.4^{d}	18.8^{a}
Number of species	4	5	5	7	4	7
2019						
Avena fatua L.	2.6^{b}	1.8^{c}	3.0^{b}	2.8^{b}	–	4.3^{a}
Cirsium arvense (L.) Scop.	–	–	0.2	0.8	–	–
Fallopia convolvulus (L.) A. Löve	0.8^{b}	1.2^{b}	$2.2^{a.b}$	3.0^{a}	2.8^{a}	3.8^{a}
Papaver rhoeas L.	2.8^{a}	1.9^{b}	2.4^{b}	1.8^{b}	3.2^{a}	4.2^{a}
Viola arvensis Murray	–	0.8^{b}	–	2.2^{a}	2.0^{a}	3.2^{a}
Number of weeds per 1 m^2	6.2^{d}	5.7^{d}	7.8^{c}	10.6^{b}	8.0^{c}	15.5^{a}
Number of species	3	4	4	5	3	4
2020						
Apera spica-venti (L.) P. Beauv.	–	–	–	0.8^{a}	0.2^{b}	1.6^{a}
Avena fatua L.	0.8^{c}	1.6^{c}	1.0^{c}	2.8^{b}	0.8^{c}	4.6^{a}
Fallopia convolvulus (L.) A. Löve	–	2.8^{a}	3.6^{a}	–	–	3.0^{a}
Galium aparine L.	3.0^{a}	2.8^{a}	$2.3^{a.b}$	4.6^{a}	2.0^{b}	0.8^{c}
Papaver rhoeas L.	3.0^{b}	3.2^{b}	7.0^{a}	5.5^{a}	2.0^{b}	4.8^{a}
Stellaria media (L.) Vill.	–	1.2^{c}	–	4.3^{a}	3.0^{b}	2.2^{b}
Number of weeds per 1 m^2	6.8^{c}	11.6^{b}	13.9^{b}	18.0^{a}	8.0^{c}	17.0^{a}
Number of species	3	5	4	5	5	6

CT – conventional tillage, RT – reduced tillage, NT – no-tillage, S – straw, WS – without straw. Different letters in line significant differences, $p < 0.05$.

The shannon-wiener's diversity index

The tillage system and crop residues influenced also the biodiversity of weeds infesting barley stands (Tab. 9). In term T_1, significantly greater weed biodiversity was noted in the RT than the NT system, on the WS than the S plots as well as in 2018 and 2020 than in 2019.

In term T_2, greater weed diversity was determined on the WS than S plots, and also in 2018 and 2019 than in 2020.

Before barley harvest (term T_3), greater weed diversity was noted on the WS than the S plots.

Table 9. The Shannon-Wiener's diversity index (*H'*)

Specification	T_1	T_2	T_3
tillage system (TS)			
CT	0.63^a	0.56^a	0.51^a
RT	0.71^a	0.60^a	0.60^a
NT	0.46^b	0.63^a	0.56^a
Mean	0.60	0.60	0.56
crop residue (CR)			
S	0.53^b	0.54^b	0.48^b
WS	0.67^a	0.66a	0.63^a
Mean	0.60	0.60	0.56
years (Y)			
2018	0.64^a	0.74^a	0.54^a
2019	0.53^b	0.67^a	0.54^a
2020	0.63^a	0.39^b	0.59^a
Mean	0.60	0.60	0.56
ANOVA			
TS	*	ns	ns
CR	**	*	*
Y	*	*	ns
TS × CR	ns	*	ns
TS × Y	ns	ns	ns
CR × Y	ns	ns	ns
TS × CR × Y	ns	ns	ns

CT – conventional tillage, RT – reduced tillage, NT – no-tillage; S – straw, WS – without straw, TS – tillage system, CR – crop residue. Different letters indicate significant differences. Significant effects: $p < 0.05$ (*), $p < 0.01$ (**), ns – not significant.

DISCUSSION

Tillage aim is to ensure optimal soil preparation for plant sowing. Until recently, this could be achieved by tillage with a muldboard plough; however, today it is replaced by different variants of the no-till system [Lal et al. 2007, Derpsch et al. 2010]. In the middle of the 20th century, the use of plows, tractors, and machines coupled with the application of fertilizers contributed to a 3–5-fold increase in crop yields and to a significant peak in farmers' incomes [Lal et al. 2007]. Today's solutions concerning the construction of tools and cultivation machines allow the plough to be replaced with units for no-till and strip-till cultivation systems. These solutions are deployed mainly in large areas where the field is prepared for sowing and sowing is performed during one pass of the cultivation unit [Morris et al. 2010, Jaskulska et al. 2018]. They are economically and organizationally viable as they enable sowing on large areas of fields in a short time, thereby significantly saving the financial outlays for cultivation. They also protect the soil against erosion and losses of organic matter and humus, and ensure water retention in the soil [Dębska et al. 2020, Pranagal and Woźniak 2021], thereby eliciting a positive effect on the biological properties of the soil [Tabagio et al. 2008, Zikeli et al. 2013, Woźniak 2019]. Investigations conducted by many authors [De Vita et al. 2007, Celik et al. 2011, Farooq et al. 2011, Jug et al. 2011] have shown that, in the regions with small precipitation, cereals produce higher grain yields in the no-till system, whereas in the regions with moderate precipitation – in the conventional system. Gruber et al. [2012] who compared crop yields in different tillage systems found that no particular tillage system was better than the other, but each system was perfectly suited to the specific soil, weather, and technical conditions of the farm. In the present study conducted on moderately moist soils, spring barley produced a higher grain yield in the RT than in the NT system, although the RT plots were more infested by weeds. It can be assumed that the density and biomass of weeds were so low that they did not compete with barley. This can be indicated by the highest spike number per 1 m^2 and 1000 grain weight determined on RT plots. At the same time, grain mass per spike was comparable in CT, RT, and NT systems, which is indicative of similar conditions in all tillage systems tested. This was also corroborated by weed biodiversity, which was similar at barley tillering stage and before harvest. Adeux et al. [2019] claimed that not all weed communities generate grain yield losses and that those with a more diversified species composition can even alleviate these losses. This indicates that weed community diversity mitigates the adverse effects of competing and prevailing species on crop yield. Also Storkey and Neve [2018] were of the opinion that a more diversified weed community is less competitive to crops.

Another issue addressed in the present study was the effect of crop residues (straw) on barley grain yield and weed infestation. A higher grain yield was obtained on the plots with the left crop residues than on those without the residues, which was due to a higher spike number per 1 m^2 and a higher 1000 grain weight. The weed number and air-dry weight of weeds were also significantly higher on the S than WS plots. At the same time, the crop residues (S) eliminated some weed species, as indicated by lesser weed diversity on these plots compared to the plots without the residues (WS). According to Tørresen and Skuterud [2002] as well as Gruber and Claupein [2009], the no-tillage system increases the bank of diaspores in the topsoil, which ultimately leads to greater crop stand infestation by weeds. Weed infestation may be reduced by mechanical tillage, during which small weed seeds with a short resting period are moved into deeper layers, from where only a few germinate [Riemens et al. 2007, Santín-Montanyá et al. 2016] or can be effectively suppressed by crop residues left on the field surface [Lu et al. 2000]. This leads to reduced crop infestation by weeds. As evidenced by previous investigations [Cline and Silvernail 2001, Cherr et al. 2006, Malhi et al. 2006, Maillard et al.

2016], the main advantages of mulching include an increase in organic matter resources and the supply of nutrients. The slow release of nitrogen from crop residues is well synchronized with nitrogen uptake by plants. This allows reducing nitrogen losses caused by its elution from the soil [Cherr et al. 2006, Cline and Silvernail 2001, Kobierski et al. 2020]. Ultimately, it can be concluded that the crop residues are an important element promoting crop yields and positively affecting the soil environment [Wicks et al. 1994, Lal 1995, Głąb and Kulig 2008].

CONCLUSIONS

A higher grain yield of spring barley was determined on RT than NT plots. The RT system also allowed producing a higher spike number per 1 m^2 and a higher 1000 grain weight. A higher grain yield was also obtained on the plots with post-harvest residues (S) than on those without the residues (WS). In addition, the S plots produced a higher barley spike number per 1 m^2 and a higher 1000 grain weight than the WS plots.

Greater weed density in barley stands was determined on the RT and NT plots without crop residues (WS), whereas smaller one – on the CT plots with the residues (S). Also the air-dry wight of weeds was higher on the NT plots without crop residues (WS) than on the other plots, while the lowest air-dry weight of weeds was determined on the CT plots with the residues (S). The biodiversity of weeds in barley stands was greater on the WS than S plots.

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