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ORIGINAL PAPER

Effect of agronomic practices on yield, grain quality and root infestation by *Gaeumannomyces graminis* var. *tritici* of winter wheat*

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Abstract

The yielding and yield quality are affected by interactions of complex dependencies between the plant, the habitat, and the agricultural practice. The goals of this study were to determine grain yield, grain quality, and winter wheat root infestation by *Gaeumannomyces graminis* var. *tritici* in crop rotation and monoculture. The experiment was established with the method of equivalent subblocks (25 m × 6 m) in three replications. The main experimental factor was the cropping systems (CS), and the second-order experimental factor was the tillage systems (TS). Winter wheat was sown in the following crop rotations: (i) CR-A: potato – winter wheat – peas – winter barley; (ii) CR-B: peas – winter barley – winter wheat – spring wheat; and (iii) MON: multi-year wheat monoculture. The following tillage systems were applied in CR-A, CR-B, and MON: (a) conventional tillage (CT); (b) reduced tillage (RT); and (c) no-tillage (NT). Wheat grain yield was affected by CS more than by TS; its highest value was recorded in CR-A followed by CR-B, whereas the lowest one – in MON. Higher grain yield was also obtained in NT and RT than in CT. The CR-A and CR-B as well as CT systems were found to elicit positive effects on the gluten content of wheat grain, grain weight per volume, Zeleny's sedimentation index, grain uniformity, and ash content of the grain. Wheat root infestation by *Gaeumannomyces graminis* var. *tritici* was more severe in MON than in CR-A and CR-B, and in NT than in CT and RT.

Keywords: quality parameters of grain, mineral composition, cropping system, tillage system, take-all disease.

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INTRODUCTION

Yield and its quality are affected by interactions of complex dependencies between the plant, the habitat, and the agronomic practice. The knowledge of these dependencies enables increasing plant productivity and modelling yield quality (Chauhan 2012, Woźniak 2019). Plant productivity is also affected by yield-limiting factors, like poor soil fertility, shortage or excess of atmospheric precipitation as well as extremely low or high temperatures (Gomez-Becerra et al. 2010). Also, crops compete with weeds at every stage of growth (MacLaren et al. 2020) and are continuously exposed to pests (Hakala et al. 2008, Jalli et al. 2021) and diseases (Janvier et al. 2007, Bailey et al. 2009). As Oerke (2006) reports, weeds decrease global crop harvests by approximately 34%. The productivity of cereals is also diminished by take-all diseases (Kurowski, Adamiak 2007, Ramanauskienė et al. 2019). As reported by Freeman and Ward (2004), diseases induced by *Gaeumannomyces graminis* are the major diseases of wheat roots. Strong infestation with this fungus is observed on fields where wheat is often sown after itself, especially in monoculture (Andrade et al. 2011).

In turn, fertilization is one of the agronomic practices that directly affect plant productivity. Several studies (Johansson et al. 2001, Woźniak, Gos 2014, Rachoń et al. 2015) have demonstrated a 30-50% yield-enhancing effect of nitrogen fertilizers applied in cereal cultivation. However, grain yield increase was also found to depend on plant species, tillage system, previous crop, protection against agrophages, and weather conditions. Crop rotation is a factor which consolidates all agrotechnical measures (Bàrberi 2002, Montemurro, Maiorana 2014). Woźniak (2021) demonstrated over 20% higher crop productivity in the crop rotation with legumes than in the one with only cereals.

Plant productivity is also influenced by tillage systems (Woźniak et al. 2015). Previous investigations (López-Bellido et al. 1996, Döring et al. 2005, De Vita et al. 2007, Peigné et al. 2007, Siddique et al. 2012, Soane et al. 2012) have shown that no-tillage with mulch left on field surface proves best on soils exposed to erosion, arid, and poor in organic matter. This is mainly the case in semi-arid regions, where the water retention in the soil ensures a certain degree of drought resistance and an evident level of economically viable yields. On moderately humid soil, better production effects are achieved by the conventional tillage system (Lahmar 2010, Morris et al. 2010, Gruber et al. 2012). Tillage systems affect also grain quality (Johansson et al. 2001, Gomez-Becerra et al. 2010). In the study by De Vita et al. (2007) conducted on light and arid soil, grain of proper technological quality was produced in the no-tillage than in the conventional tillage system. In turn, Woźniak and Gos (2014) as well as Woźniak et al. (2018) demonstrated that various tillage systems applied on moderately moist soil caused insignificant differences in grain quality. In addition, they showed that protein and gluten contents of the grain depended mainly on nitrogen fertilization, with a higher fertilization rate increasing contents of both grain components.

The goals of this study were to determine grain yield, grain quality, and winter wheat root infestation by *Gaeumannomyces graminis* var. *tritici* in two crop rotations and monoculture, and three tillage systems. Research hypotheses were formulated based on literature data assuming that crop succession in crop rotations and tillage systems trigger significant differences in: (a) winter wheat yield and grain quality; (b) wheat infestation by take-all diseases. In addition, it may be assumed that the best productive effects are ensured by crop rotation with root plants and legumes and by the conventional tillage system.

MATERIALS AND METHODS

Experiment localization and scheme

A field experiment was established in 2000 at the Uhrusk Experimental Farm belonging to the University of Life Sciences in Lublin (south-eastern Poland, 51°18′ N, 23°36′ E). The results presented in the manuscript derived from 2019-2021. The experiment was established in the system of equalized subblocks (25 m × 6 m) in three replications. The main experimental factor was cropping system (CS), whereas the second-order experimental factor was tillage systems (TS). Winter wheat of 'Dakotana' cultivar was sown in the following crop rotations: (i) CR-A: potato – winter wheat – peas – winter barley; (ii) CR-B: peas – winter barley – winter wheat – spring wheat; and (iii) MON: long-term winter wheat monoculture (Table 1). The following tillage systems were applied in CR-A, CR-B, and MON: CT – conventional tillage; RT – reduced tillage; and NT – no-tillage (Tables 2 and 3).

Table 1

Previous crops – varieties, dates of sowing and harvesting

Crops	Variety	Date of sowing	Date of harvest
Potato	Lord	third week of April	first week of September
Winter wheat	Dakotana	last week of September	first or second week of August
Pea	Batuta	first week of April	third or fourth week of July

Table 2

Scheme of soil tillage for winter wheat in crop rotation A
(CR-A: potato – winter wheat – peas – winter barley)

Crops	Soil tillage
After potato harvest	cultivator and harrowing
Pre-sowing cultivation	tillage unit for pre-sowing (cultivation and string roller)

Table 3

Scheme of soil tillage for winter wheat in crop rotation B
(CR-B: peas – winter barley – winter wheat – spring wheat)
and winter wheat monoculture (MON)

Crops	Tillage system		
	CT (conventional tillage)	RT (reduced tillage)	NT (no-tillage)
After harvesting winter barley (CR-B) After harvesting winter wheat (MON)	shallow ploughing (depth of 10 cm) and harrowing	cultivator (twice)	Glyphostate 4 L ha^{-1} (360 g L^{-1})
Pre-sowing cultivation	pre-sow ploughing (depth of 18-22 cm)	tillage unit for pre-sowing (cultivation and string roller)	

On CT plots, shallow ploughing and harrowing were performed after previous crop harvest, and pre-sowing ploughing at a depth of 18-22 cm two weeks before winter wheat sowing. On RT plots, shallow ploughing was replaced by cultivating, whereas pre-sowing ploughing – by a cultivation unit comprising a cultivator and string roller. In the NT system, mechanical cultivation was replaced by administration of a glyphosate-containing herbicide (4 L ha^{-1}), whereas wheat was sown using a cultivation-sowing unit. Winter wheat was sown in the last of week of September, at the sowing density of 380 seeds per m^2. Before sowing, the soil was fertilized with 20 kg N ha^{-1}, 35 kg P ha^{-1}, and 90 kg K ha^{-1}. Nitrogen fertilizers were applied in three terms in the springtime: 1) 75 kg N ha^{-1} at the tillering stage; 2) 45 kg N ha^{-1} at the shooting stage; and 3) 20 kg N ha^{-1} at the onset of the ear formation stage.

Winter wheat was protected from fungal diseases by means of fungicides composed of flusilazole + carbendazim (Alert 375 SC – 1 L ha^{-1}) applied at the tillering stage, and propiconazole + phenpropidine (Tilt Turbo 575 EC – 1 L ha^{-1}) applied at the shooting stage. Weeds were eradicated using herbicides containing a mixture of the following active substances MCPA + mecoprop + dicamba (Chwastox Trio 540 SL – 1.5 L ha^{-1}) and fenoxaprop-P-ethyl (Puma Uniwersal 069 EW – 1 L ha^{-1}) at the tillering stage.

Soil and weather conditions

The soil the experiment was established on was Rendzic Phaeozem (IUSS Working Group WRB 2015) with the following mineral fraction distribution: sand (2.0-0.05 mm) 53%; silt (0.05-0.002 mm) 24%; and clay (<0.002 mm) 23%. Total nitrogen content in the 25 cm soil layer was 0.68 g kg^{-1}, that of available phosphorus (P) was 120 mg kg^{-1}, that of potassium (K) was 219 mg kg^{-1}, that of magnesium (Mg) was 68 mg kg^{-1}, and that of organic C was 12 g kg^{-1}. The soil is slightly alkaline (pH_{KCl} = 7.2).

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. The annual sum of precipitation ranged from 515 to 522 mm, including from

337 mm to 346 mm rainfalls recorded in the spring and summer months (since April till September), and from 158 mm to 184 mm in the autumn and winter months (since October till March) – Figure 1. The highest air temperatures were recorded in June, July, and August, whereas the lowest ones were in December, January, and February (Figure 2).

Production traits

The scope of the study included determinations of winter wheat grain yield and its components (spike number per m^2, grain weight per spike, 1000 grain weight); quality traits of the grain (total protein content, wet gluten content, Zeleny's sedimentation index, grain weight per volume, grain uniformity); ash content and mineral composition of the grain (including contents of phosphorus, potassium, magnesium, manganese, iron, copper, zinc); and the index of wheat root infestation by *Gaeumannomyces graminis* var. *tritici*.

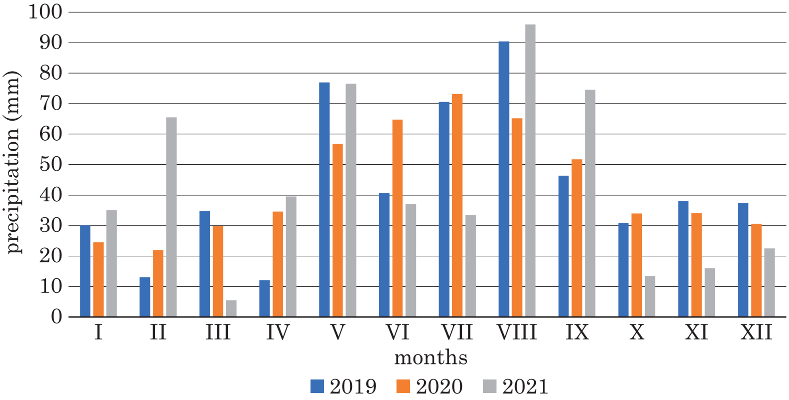

Fig. 1. Average monthly precipitation

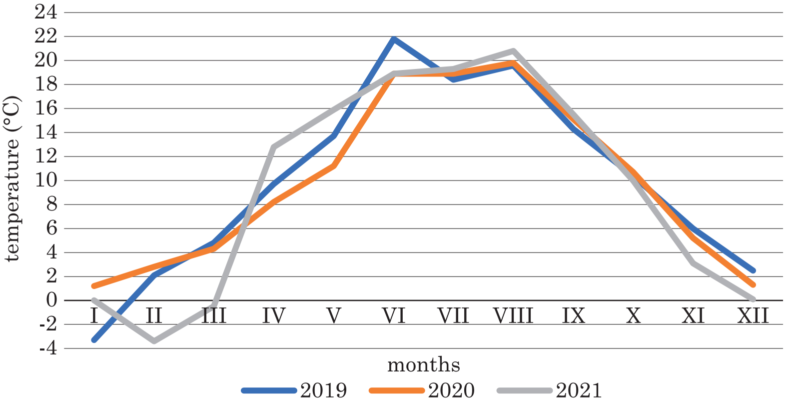

Fig. 2. Average monthly air temperature

Wheat grain was harvested using a plot harvester. The number of spikes was counted at each plot on the area of m^2. Grain weight per spike was determined using 40 spikes randomly selected from each plot, whereas 1000 grain weight was established by counting and weighing 2×500 grains.

Total protein content and wet gluten content of the grain as well as the Zeleny's sedimentation index were determined using near-infrared spectroscopy (NIRS) on an Inframatic 9200 apparatus. The grain weight per volume was measured using a 1-L densitometer, whereas grain uniformity was determined using a sorter with a mesh size of 2.5 mm x 25 mm.

The contents of ash and minerals in wheat grain were determined after dry mineralization of the samples at a temp. of 600°C. The ash obtained was dissolved in 5 mL of 6 M HCL, and the solution was filled up with distilled water to the volume of 50 mL. Measurements were conducted with the method of atomic absorption spectrometry excited in air/acetylene flame, in three replications per plot.

Take-all disease of winter wheat

Plant infestation by *Gaeumannomyces graminis* var. *tritici* was evaluated in the spring at the wheat tillering stage. The evaluation consisted of digging out 40 plants from each plot, carefully washing their root system, and assessing the health status of plants by classifying them as: (a) healthy plants, (b) slightly infested plants, (c) moderately infested plants, (d) severely, and (e) very severely infested plants; and computing the root infestation index (*Ip*) from the following formula (according to EPPO):

$$lp = \frac{[(a\times 0)+(b\times 10)+(c\times 30)+(d\times 60)+(e\times 100)]}{n}$$

where *a* –number of healthy plants; *b* –number of slightly infested plants (1-10%); *c* – number of moderately infested plants (11-30%); *d* –number of severely infested plants (31-60%); *e* –number of very severely infested plants (61-100%); and $n - (a + b + c + d + e)$ = total number of evaluated plants.

Statistical analysis

The results were subjected to the analysis of variance (ANOVA), whereas the significance of differences between mean values for cropping system (CS), tillage systems (TS), study years (Y), and their interactions was determined with the Tukey's HSD test, $P<0.05$.

RESULTS

Grain yield and its components

Wheat produced the highest grain yield in crop rotation CR-A when grown after potato, a lower yield in CR-B after winter barley (by 10.6%), and the lowest one (by 58.6%) in the monoculture (Table 4). Higher grain yields were also recorded in NT and RT systems than in CT, i.e. by 18% and 8.1%, respectively. Differences in grain yield also occurred between study years, with a higher yield noted in 2021 than in 2019 (by 25.9%). The evaluation of variance analysis components demonstrated that the wheat grain yield was affected to a greater extent by CS than by TS and Y as well as by CS × TS than by the other interactions studied (Table 5).

Table 4

Grain yield of winter wheat and its components

Specification	Grain yield (t ha^{-1})	Spike number per m^2	Grain weight per spike (g)	1000 grain weight (g)
Cropping system (CS)				
CR-A	7.50^{a}	454^{a}	1.66^{a}	47.4^{a}
CR-B	6.78^{b}	502^{a}	1.35^{b}	47.4^{a}
MON	4.73^{c}	481^{a}	0.98^{c}	44.3^{b}
Tillage systems (TS)				
CT	5.83^{b}	455^{a}	1.28^{b}	47.9^{a}
RT	6.30^{a}	486^{a}	1.30^{b}	46.1^{b}
NT	6.88^{a}	496^{a}	1.42^{a}	45.3^{c}
Year (Y)				
2019	5.49^{b}	470^{a}	1.31^{b}	44.9^{b}
2020	6.62^{ab}	477^{a}	1.28^{b}	45.3^{b}
2021	6.91^{a}	490^{a}	1.41^{a}	49.0^{a}

CR-A: potato – winter wheat – peas – winter barley; CR-B: peas – winter barley – winter wheat – spring wheat; MON: multi-year wheat monoculture; CT – conventional tillage; RT – reduced tillage; NT – no-tillage. Different letters indicate significant differences, $p<0.05$.

The experimental factors caused no significant differences in spike number per m^2, although a higher spike number was noted in CR-B than in CR-A and MON as well as in NT and RT systems than in CT. In contrast, CR, TS, and Y caused significant differences in grain weight per spike. In CR-A, it was higher by 41% than in MON and by 18.7% than in CR-B. In addition, a higher grain weight per spike was determined on NT than CT and RT plots as well as in wheat harvested in 2021 compared to the other study years. The 1000 grain weight of wheat was higher in CR-A and CR-B than in MON. Its value was also differentiated by tillage systems, i.e. higher

Table 5

Analysis of variance (*F* values) for winter wheat yield and yield components

Specification	Value	CS	TS	Y	CS × TS	CS ×Y	TS × Y	CS × TS × Y
Grain yield	*F*	1731.8	230.3	39.8	204.4	19.1	43.2	18.2
	p	**	**	*	*	ns	*	ns
Spike number	*F*	3.15	5.10	2.12	4.29	2.13	1.20	1.78
	p	ns	ns	ns	ns	ns	ns	ns
Grain weight per spike	*F*	141.0	6.43	7.2	14.2	2.12	1.68	2.01
	p	**	*	*	**	ns	ns	ns
1000 grain weight	*F*	35.0	19.9	8.9	7.08	3.12	5.91	2.71
	p	**	**	*	*	ns	*	ns

Significant effects: $p<0.05$ (*), $p<0.01$ (**), ns – not significant

1000 grain weight was achieved in CT than in RT and NT systems. In addition, a higher 1000 grain weight was produced by plants in 2021 than in 2019 and 2020. The evaluation of variance analysis components indicated that the grain weight per spike and the 1000 grain weight were more strongly influenced by CS than by TS and Y.

Grain quality and mineral composition

The protein content of wheat grain was differentiated only by study years (Table 6). A higher protein content was found in the grain harvested in 2019 than in that from 2020. In turn, the gluten content of the grain depended on CS, TS, and Y, and was higher in the grain harvested from CR-A than from MON plots, and also from CT than from NT plots. Its higher value was also determined in the grain from 2019 compared to that from the other study years. The Zeleny's sedimentation index values were higher in CR-A and CR-B than in MON as well as in 2019 compared to the other study years. Likewise, greater grain weight by volume was determined in the grain harvested from CR-A and CR-B plots than from MON as well as in CT and RT systems compared to NT. In addition, its higher values were recorded in 2019 and 2020 than in 2021. Analogous observations were made for grain uniformity. More uniform was the grain harvested from CR-A and CR-B plots than from MON, and that produced in CT and RT systems compared to NT. Significantly better grain uniformity was also determined in 2019 and 2020 than in 2021 (Table 7).

A significantly higher ash content was assayed in the wheat grain harvested in MON, compared to crop-rotations CR-A and CR-B (Table 8). More ash was also found in the grain from NT than from CT and RT systems as well as in that harvested in 2020 compared to 2019. The high ash content of the grain was also due to MON × NT and NT × Y interactions (Table 9).

Table 6

Quality parameters of winter wheat grain

Specification	Total protein content (%)	Wet gluten content (%)	Zeleny's sedimentation index (mL)	Grain weight per volume (kg hL^{-1})	Grain uniformity (%)
Cropping system (CS)					
CR-A	13.6^{a}	28.3^{a}	35.1^{a}	69.2^{a}	88.6^{a}
CR-B	13.4^{a}	28.1^{ab}	34.9^{a}	68.6^{a}	87.7^{a}
MON	13.4^{a}	27.4^{b}	34.0^{b}	65.2^{b}	83.5^{b}
Tillage systems (TS)					
CT	13.5^{a}	28.3^{a}	35.1^{a}	69.0^{a}	88.3^{a}
RT	13.5^{a}	28.0^{ab}	34.7^{a}	68.3^{a}	87.4^{a}
NT	13.4^{a}	27.6^{b}	34.2^{a}	65.7^{b}	84.1^{b}
Year (Y)					
2019	13.9^{a}	31.5^{a}	37.7^{a}	69.2^{a}	91.0^{a}
2020	13.0^{b}	26.0^{b}	32.0^{b}	69.0^{a}	88.5^{a}
2021	$13.5^{a,b}$	26.4^{b}	34.3^{b}	64.8^{b}	80.3^{b}

CR-A: potato – winter wheat – peas – winter barley; CR-B: peas – winter barley – winter wheat – spring wheat; MON: multi-year wheat monoculture; CT – conventional tillage; RT – reduced tillage; NT – no-tillage. Different letters indicate significant differences, $p<0.05$

Table 7

Analysis of variance (F values) for quality of winter wheat grain

Specification	Value	CS	TS	Y	CS × TS	CS ×Y	TS × Y	CS × TS × Y
Total protein	F	2.83	0.81	6.12	2.35	1.98	1.08	3.11
	p	ns	ns	*	ns	ns	ns	ns
Wet gluten	F	5.42	4.76	4.92	2.91	2.05	1.90	3.41
	p	*	*	*	ns	ns	ns	ns
Zeleny's sedimentation index	F	6.51	2.76	7.12	1.18	0.98	2.05	2.93
	p	*	ns	*	ns	ns	ns	ns
Grain weight per volume	F	7.46	5.04	6.37	1.13	2.04	0.98	1.60
	p	*	*	*	ns	ns	ns	ns
Grain uniformity	F	8.30	5.60	7.12	1.10	0.79	0.90	10.12
	p	*	*	*	ns	ns	ns	*

Significant effects: $p<0.05$ (*), $p<0.01$ (**), ns – not significant

The content of phosphorus (P) in the grain was differentiated only by study years. Its higher value was determined in the grain harvested in 2020 compared to the other study years. In turn, the potassium content

Table 8

Mineral composition of winter wheat grain

Specification	Total ash (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})
Cropping system (CS)								
CR-A	14.9^{b}	3.58^{a}	3.98^{a}	1.20^{a}	36.4^{b}	$49{,}0^{a}$	2.45^{a}	21.0^{a}
CR-B	14.6^{b}	3.51^{a}	3.83^{b}	1.18^{a}	34.1^{c}	$40{,}5^{b}$	2.40^{a}	20.9^{a}
MON	15.9^{a}	3.56^{a}	3.85^{b}	1.18^{a}	37.9^{a}	37.6^{b}	2.20^{b}	17.6^{b}
Tillage systems (TS)								
CT	14.9^{b}	3.52^{a}	3.89^{a}	1.16^{a}	36.4^{a}	46.0^{a}	2.48^{a}	20.3^{a}
RT	14.8^{b}	3.57^{a}	3.82^{b}	1.20^{a}	35.9^{a}	40.1^{b}	2.32^{b}	19.5^{b}
NT	15.6^{a}	3.56^{a}	3.90^{a}	1.20^{a}	36.1^{a}	41.0^{b}	2.24^{b}	19.6^{b}
Year (Y)								
2019	14.6^{b}	$3{,}55^{b}$	3.88^{b}	1.09^{c}	37.0^{a}	43.9^{a}	2.39^{a}	20.9^{a}
2020	15.6^{a}	3.61^{a}	3.97^{a}	1.19^{b}	36.5^{a}	44.1^{a}	2.30^{a}	19.1^{a}
2021	15.1^{ab}	3.49^{b}	3.76^{c}	1.28^{a}	34.9^{b}	39.1^{a}	2.33^{a}	19.4^{a}

CR-A: potato – winter wheat – peas – winter barley; CR-B: peas – winter barley – winter wheat – spring wheat; MON: multi-year wheat monoculture; CT – conventional tillage; RT – reduced tillage; NT – no-tillage. Different letters indicate significant differences, $p<0.05$

Table 9

Analysis of variance (F values) for mineral composition of winter wheat grain

Specification	Value	CS	TS	Y	CS × TS	CS ×Y	TS × Y	CS × TS × Y
Total ash	F	5.08	4.14	6.12	8.29	1.12	7.90	0.78
	p	*	*	*	*	ns	*	ns
P	F	0.97	0.62	8.20	1.12	0.90	2.01	1.10
	p	ns	ns	*	ns	ns	ns	ns
K	F	8.29	7.36	7.04	1.01	8.10	1.30	9.10
	p	**	**	*	ns	*	ns	*
Mg	F	0.39	0.51	6.31	1.12	1.00	0.90	0.79
	p	ns	ns	*	ns	ns	ns	ns
Mn	F	7.78	0.18	6.40	1.18	0.91	0.83	1.90
	p	**	ns	*	ns	ns	ns	ns
Fe	F	223.1	64.9	6.12	21.8	0.90	1.23	1.16
	p	**	**	ns	**	ns	ns	ns
Cu	F	17.98	18.18	1.71	9.49	0.98	1.14	1.66
	p	**	*	ns	**	ns	ns	ns
Zn	F	72.26	5.37	0.91	6.01	1.10	0.87	0.73
	p	**	*	ns	**	ns	ns	ns

Significant effects: $p<0.05$ (*), $p<0.01$ (**), ns – not significant of the grain was differentiated by both CS, TS, and Y. More potassium (K) was found in the grain from CR-A than in that from CR-B and MON, as well as in that from CT and NT than from RT. Its higher content was also determined in the grain harvested in 2020 compared to the other study years. The magnesium (Mg) content of wheat grain was differentiated only by study years, and was the highest in the grain harvested in 2021, followed by that harvested in 2020, and the lowest in the grain from 2019. The crop rotation were also found to cause differences in the manganese (Mn) content of the grain. Its significantly higher content was determined in the grain from MON than in that from CR-A and CR-B. More manganese was also found in the grain harvested in 2019 and 2020 compared to that from 2021. In turn, the iron (Fe) content of the grain was affected by CS and TS. More iron (Fe) was found in the grain from CR-A than in that from CR-B and MON, as well as in the grain from CT compared to RT and NT.

Also, the copper (Cu) and zinc (Zn) contents were found to depend on CS and TS. Significantly higher contents of these microelements were determined in the grain harvested from CR-A and CR-B plots than from MON, as well as in the grain from CT system compared to RT and NT. Also, the CR-A × CT interaction contributed to their higher contents in the grain compared to the other interactions tested.

Take-all disease of wheat

The value of the index of wheat root infestation by *G. graminis* var. *tritici* was significantly higher in MON than in CR-A and CR-B (Table 10). Wheat roots were also more severely infested in the NT than CT and RT systems, and also in 2019 than in the other study years. Wheat root infestation by *G. graminis* var. *tritici* was promoted by MON × NT interaction, especially in 2019. The evaluation of variance analysis components indicated that wheat infestation was affected to a greater extent by CS than by TS and Y.

DISCUSSION

Ample research (Malhi, Lemke 2007, Chauhan 2012, Rachoń, Woźniak 2020) has shown that the results of analyses of the impact of individual factors on crop yielding are inexplicit because their ultimate outcomes are additionally determined by other agroengineering and weather factors. In the present study, wheat grain yield was affected to a greater extent by cropping system (CS) than by tillage systems (TS) and study years (Y). Wheat productivity was also influenced by CS × TS and TS × Y interactions. This is undoubtedly due to the fact that crop rotation integrates all agrotechnical measures typical of crops cultivated in this system (Babublicovà 2016, Woźniak 2021). Various plant species grown in the crop rotation system

Table 10

Index of winter wheat root infestation by *Gaeumannomyces graminis* var. *tritici*

Specification	Index	Value	
		F	*p*
Cropping system (CS)			
CR-A	0.97^{b}		
CR-B	1.58^{b}	618.9	**
MON	2.79^{a}		
Tillage systems (TS)		195.6	**
CT	1.36^{b}		
RT	1.61^{b}		
NT	2.36^{a}		
Year (Y)		28.7	*
2019	2.21^{a}		
2020	1.51^{b}		
2021	1.61^{b}		
CR × TS		5.12	ns
CR × Y		16.4	*
TS × Y		3.10	ns
CR × TS × Y		5.82	ns

CR-A: potato – winter wheat – peas – winter barley; CR-B: peas – winter barley – winter wheat – spring wheat; MON: multi-year wheat monoculture; CT – conventional tillage; RT – reduced tillage; NT – no-tillage. Different letters indicate significant differences. Significant effects: $p<0.05$ (*), $p<0.01$ (**), ns – not significant

protect crop stands against pests (Oerke 2006, Ratnadass et al. 2012), diseases (Andrade et al. 2011, Ramanauskienė et al. 2019), and weeds (Hiltbrunner et al. 2007, Kruidhof et al. 2009, Boselli et al. 2021). The cropping system (CS) also affected wheat infestation by *G. graminis*. The value of the infestation index was significantly higher in MON than in CR-A and CR-B. Wheat was also more severely infested in the NT than in the CT and RT systems. The study results indicate a significantly stronger impact of CS than TS on crop infestation by *G. graminis*. This observation is consistent with findings reported by other authors (Bailey et al. 2009, Andrade et al. 2011, Jenkyn et al. 2014). The factors affecting the growth and development of plants determine grain quality and mineral composition (Gomez-Becerra et al. 2010, Rachoń et al. 2015, Woźniak et al. 2018). Also, the present study demonstrated the beneficial effect of crop rotation and conventional tillage on the quality parameters of wheat grain (gluten content, grain weight per volume, Zeleny's sedimentation index, and grain uniformity).

CONCLUSIONS

The grain yield of winter wheat was affected to a greater extent by crop rotation than tillage systems. In addition, winter wheat produced a higher grain yield in crop rotation than in monoculture as well as in no-tillage than in conventional tillage system. Crop rotation and no-tillage system were found to positively affect the gluten content, grain weight per volume, Zeleny's sedimentation index, grain uniformity, and mineral composition of the grain. Wheat root infestation by *Gaeumannomyces graminis* var. *tritici* was more severe in the monoculture than in crop rotations, as well as in the no-tillage system than in conventional and reduced tillage systems.

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