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ORIGINAL ARTICLE / ORIGINALBEITRAG

The Effect of Foliar Fertilization with Micronutrients on the Incidence and Severity of Leaf and Stem-base Diseases in Winter Triticale (x *Triticosecale* Witmm.) and Winter Rye (*Secale cereale* L.)

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Abstract

Winter triticale (*Triticale*) cv. Dinaro and winter rye (*Secale cereale* L.) cv. Dańkowskie Diament were grown in 2012 and 2013 in a field-plot experiment in Tomaszkowo near Olsztyn (NE Poland). The experiment consisted of 7 treatments: absolute control (without fertilizers or the growth stimulator), control-NPK fertilizer, NPK fertilizer + micronutrients applied alone or in combination (4 treatments), NPK fertilizer + Nano-Gro growth stimulator. The severity of disease symptoms on the leaves and stem-bases of triticale and rye was evaluated throughout the growing season. Symptoms of powdery mildew on the leaves of winter triticale and winter rye were noted only in the growing season of 2013, and disease severity remained at a low level. In the growing season of 2012, weather conditions were conducive to the spread of *Septoria tritici* blotch (STB) and brown rust on triticale (the highest values of infection index were 41.6 and 23.8%, respectively), and scald and brown rust on rye (29.0 and 38.1%, respectively). Foliar application of micronutrients influenced the rates of infections caused by *Zymoseptoria tritici* and *Puccinia recondita* f. sp. *tritici* on triticale leaves. Symptoms of eyespot and Fusarium foot and root rot were noted on the stem-bases of both cereal species, whereas symptoms of take-all disease and sharp eyespot were observed sporadically. Significant differences were found between treatments in the severity of infections caused by *Gaeumannomyces graminis* on the stem-bases of triticale, and by *Tapesia* spp. and *Rhizoctonia* spp. on the stem-bases of rye.

Keywords Winter triticale · Winter rye · Diseases · Yield · Micronutrients · Nano-Gro® growth stimulator

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Einfluss der Blattdüngung mit Mikronährstoffen auf Häufigkeit und Schweregrad von Blatt- und Stängelkrankheiten bei Wintertriticale (x *Triticosecale* Witmm.) und Winterroggen (*Secale cereale* L.)

Zusammenfassung

Wintertriticale (*Triticale*) der Sorte Dinaro und Winterroggen (*Secale cereale* L.) der Sorte Dańkowskie Diament wurden 2012 und 2013 in einem Feldversuch in Tomaszkowo bei Olsztyn (Polen) angebaut. Das Experiment bestand aus 7 Behandlungsmethoden: Kontrolle (ohne Düngemittel), NPK-Düngemittel; NPK-Düngemittel + Mikronährstoffe, einzeln oder in Kombination (4 Behandlungen); NPK-Düngemittel + Wachstumsstimulator Nano-Gro®. Während der Vegetationsperiode wurde die Infektion von Blättern und Stängeln der Getreidearten durch Krankheitserreger bewertet. Echter Mehltau wurde auf den Blättern von Wintertriticale und Winterroggen nur in der Vegetationsperiode 2013 mit geringem Schwerengrad festgestellt. Die in der Vegetationsperiode 2012 vorherrschenden Wetterbedingungen begünstigten die Entwicklung von Blattseptoriosis und Braunrost auf Triticale (die höchsten Werte der Infektion betrugen entsprechend 41,6 und 23,8 %) und Rhinchosporose und Braunrost auf Roggen (29,0 und 38,1 %). Die Blattapplikation von Mikronährstoffen beeinflusste die Infektionsraten von *Zymoseptoria tritici* und *Puccinia recondita* f. sp. *Tritici* auf Triticale-Blättern. An der Stängelbasis beider Getreidearten wurden Symptome von Zerbrechlichkeit und Fusariose des Getreides festgestellt und sporadisch Symptome von Stängelbasisfäule und Rhizoctoniose. Zwischen den Behandlungsmethoden wurden signifikante Unterschiede im Schweregrad von Infektionen festgestellt, die durch *Gaeumannomyces graminis* an der Stängelbasis von Triticale und durch *Helgardia* spp. und *Rhizoctonia* spp. an der Stängelbasis von Roggen verursacht wurden.

Schlüsselwörter Wintertriticale · Winterroggen · Krankheiten · Ertrag · Mikronährstoffe · Wachstumsstimulator Nano-Gro®

Introduction

Cereals, including winter triticale and winter rye, which are important in human and animal nutrition, are attacked by many pathogens. Powdery mildew of grasses and cereals is one of the most devastating fungal diseases in the world (Walker et al. 2011; Klocke et al. 2013). Troch et al. (2012) demonstrated that *Blumeria graminis* isolates from triticale were virulent against most of the tested triticale cultivars and several wheat cultivars. Triticale yield loss caused by powdery mildew may reach 15% (Czembor et al. 2014). Menardo et al. (2016) identified four *formae speciales* of *B. graminis* (*B. graminis* f.sp. *tritici* infects tetraploid wheat *Triticum durum* and hexaploid wheat *Triticum aestivum, B. graminis* f.sp. *secalis* infects rye and, to a limited extent, triticale, *B. graminis* f.sp. *triticale* infects durum wheat, common wheat, triticale and, to a limited extent, rye, and *B. graminis* f.sp. *dicocci* infects durum wheat). The causative agents of scald (*Rhynchosporium secalis*), powdery mildew (*B. graminis*) and brown rust (*Puccinia recondita*) are considered the most dangerous pathogens of rye leaves in Lithuania (Smatas and Gaurilcikiene 2005; Skuodienė and Nekrošienė 2009). According to more recent reports (Zaffarano et al. 2011), Poaceae species, including rye and triticale, are hosts for *R. secalis*, whereas *Dactylis glomerata* plants are colonized by *Rhynchosporium orthosporum*, and *Agropyron* spp. plants are hosts for *Rhynchosporium agropyri*. Eyespot is a prevalent disease in regions characterized by a cool and moist climate, including Poland, Western Europe, Southern Africa, North America and Australia (Váňová et al. 2005; Cromey et al. 2006; Głazek 2009). The prevalence of the above disease on the stem-bases of winter triticale grown in Lithuania ranged from 8.0 to 82.7%, depending on the year of study and location (Ramanauskienė et al. 2014). Another serious disease of cereals, including of triticale and rye, is Fusarium foot rot caused by *Fusarium* spp. (Dordas 2008; Kurowski et al. 2010; Bhaduri et al. 2014). In south-eastern Poland, necroses on the bottom internodes of winter triticale were in most cases caused by *F. avenaceum* and *F. culmorum* (25% of total isolates each) (Mielniczuk et al. 2012). Lemańczyk (2012) observed high variation in susceptibility to infections caused by *Rhizoctonia cerealis* and *R. solani* in winter triticale. The seedlings of the analyzed triticale cultivars were not resistant to the above pathogens. Areseniuk and Góral (2015) found that rye and wheat were more susceptible to infections than triticale. According to An et al. (2019), rye (*Secale cereale* L.) can be used as a source of disease resistance genes in wheat (*Triticum aestivum* L.) improvement programs.

Optimal macronutrient and micronutrient fertilization of crop plants, including the Poaceae family, increases their resistance to pathogens (Mann et al. 2004; Simoglou and Dordas 2006) and is the key determinant of cereal grain yields (Korzeniowska 2008; Đekić et al. 2014). Mineral fertilization affects soil pH and organic matter content, the concentrations of plant-available nutrients (Katan 2009), and plant resistance to pathogens (Shaaban 2010; Huber and Jones 2013). Cereal crops respond positively to intensive mineral fertilization, in particular to nitrogen (N) fertiliz-

Table 1 Experimental treatments

Absolute control	Without fertilization		
Control-NPK 90 kg N ha^{-1} 70 kg P_2O_5ha^{-1} 100 kg K_2O ha^{-1}	Soil fertilization		Foliar fertilization
	Before sowing	Tillering stage BBCH 22–23	Stem elongation stage BBCH 30–31
	30.2 kg P ha^{-1} (46% triple superphosphate) 83.1 kg K ha^{-1} (56% potash salt)	54.0 kg N ha^{-1} (46% of urea)	36.0 kg N ha^{-1} (10% solution of 46% of urea)
	Foliar fertilization with micronutrients; stem elongation stage BBCH 30–31		
NPK + Cu	NPK as above	0.2 kg Cu ha^{-1} (1% solution of $CuSO_4$)	
NPK + Zn		0.2 kg Zn ha^{-1} (1% solution of $ZnSO_4$)	
NPK + Mn		0.2 kg Mn ha^{-1} (0.5% solution of $MnSO_4$)	
NPK + Cu + Zn + Mn		0.2 kg Cu ha^{-1} + 0.2 kg Zn ha^{-1} + 0.2 kg Mn ha^{-1} (solution as above)	
NPK + Nano-Gro®	NPK as above; Nano-Gro® (organic growth stimulator in the form of oligosaccharide pellets containing Fe, Co, Al, Mg, Mn, Ni and Ag sulfates in a concentration of 10^{-9} mol), 8 pellets; BBCH 30–31		

ers. According to Nefir and Tabără (2011), the optimal rate of N fertilizers for triticale is 80–120 kg ha^{-1}. However, excessive N fertilization may lead to increased susceptibility to infections in delicate tissues of cereal plants (Yoshida et al. 2008). The application of K may reduce the severity of selected cereal diseases (Sharma et al. 2005). Balanced N and potassium (K) fertilization determines plant susceptibility to infectious diseases caused by pathogens. Dordas (2008) demonstrated that micronutrient fertilizers inhibited the spread of cereal diseases. More severe symptoms of infections caused by *Blumeria graminis* and *Puccinia recondita* f.sp. *secalis* were observed on winter rye leaves in manure, manure + NPK and NPK treatments, compared with the control treatment without fertilization. The types of fertilizers had no significant effect on the severity of leaf diseases. However, manure contributed to controlling the spread of *Gaeumannomyces graminis* and *Oculimacula acuformis* (Sawińska et al. 2019). Knapowski et al. (2010) pointed to a beneficial influence of combined mineral and micronutrient fertilization on grain yield. Chattha et al. (2017) informed that a combined application of Zn to soil and foliar was effective in increasing grain yield of wheat.

The aim of this study was to determine the effect of foliar fertilization with micronutrients and application of the Nano-Gro growth stimulator on the health of leaves and stem-bases of winter triticale and winter rye. The results were used to analyze the correlations between infection index and grain yield.

Material and Methods

Winter triticale (*Triticale*) cv. Dinaro and winter rye (*Secale cereale* L.) cv. Dańkowskie Diament were grown in 2012 and 2013 at the Agricultural Experiment Station near Olsztyn (53°72 N; 20°42 E) on podzolic soil of complex 4 and quality class IIIb of a granulometric composition of light loam according to FAO (IUSS Working Group WRB 2015). Soil had the following properties (analyses were performed in the Chemical and Agricultural Station in Olsztyn): pH in a 1 molar solution of KCl—4.62; C_{org} content—7.93 g kg^{-1}, N_{total} content—0.95 g kg^{-1}; plant-available minerals (mg kg^{-1}): P—58.9, K—203.4, Mg—8.1, Cu—2.5, Zn—7.9, Mn—189.0 and Fe—1800.0 (mean values for 2012–2013).

The experiment had a randomized block design with three replications. Plot sown area was 8.00 m^2 and plot harvested area was 5.20 m^2. The experiment consisted of 7 treatments (Table 1). All operations (identical in all plots) were carried out and mineral fertilizers were applied in accordance with the agronomic requirements of winter rye and winter triticale (Institute of Soil Science and Plant Cultivation-State Research Institute in Pulawy): preceding crop winter triticale in both years, date of sowing—14.09.2011 and 17.09.2012, plant density/ha: 550 (winter triticale) and 500 (winter rye), date of harvest—31.07 2012 and 2013. Foliar fertilization with micronutrients were applied according to the scheme (Table 1).

During the growing season (growth stages medium milk: grain content milky, grains reached final size, still green BBCH 75) (Meier 2001) the severity of the following leaf diseases was estimated visually (identification of external symptoms of diseases) and microscopically: winter triticale—powdery mildew (*Blumeria graminis*), Septoria leaf blotch (*Mycosphaerella graminicola,* anamorph: *Zymoseptoria tritici*) and brown rust (*Puccinia recondita* f.sp. *tritici*); winter rye—powdery mildew (*B. graminis*), scald (*Rhynchosporium secalis)* and brown rust (*Puccinia recondita* f.sp. *recondita*), using a 5-point scale (1°—up to 5% of leaf area has been infected, 2°—6 to 10% of leaf area has been infected, 3°—11 to 30% of leaf area has been infected, 4°—31 to 50% of leaf area has been infected, 5°—more than 50% of leaf area has been infected). The severity of diseases was assessed on two leaves (the flag leaf and the first leaf below the flag leaf) on 20 plants per plot. The results were presented as the infection index (below).

In the ripening growth stages (growth stages soft dough: grain content soft but dry—hard dough: grain content solid BBCH 85–87), the severity of the following stem-base diseases was estimated on 30 plants per plot (the plants, including the roots, were transported to the laboratory for accurate identification of external symptoms of diseases): take-all (*Gaeumannomyces graminis*), eyespot (*Oculimacula acuformis, O. yallundae,* anamorph: *Tapesia acuformis, T. yallundae*), Fusarium foot and root rot (*Fusarium* spp.) and sharp eyespot (*Ceratobasidium cereale* anamorph: *Rhizoctonia cerealis; Thanatephorus cucumeris* anamorph: *Rhizoctonia solani*), using a 2-point scale (0°—absence of disease symptoms, 1°—weak disease symptoms, 2°—strong disease symptoms). The results were presented as the infection index.

The infection index was expressed as percentage according to Łacicowa (1970).

$$Ii = \frac{\Sigma\,(axb)\,x\,100\%}{NxI}$$

where Σ (a · b) is the sum of the products resulting from the multiplication of the number of plants (a) by points on the five-point scale (b), N is the total number of plants and I is the highest number of points on the scale. The infection index was estimated separately for each disease. The results were processed statistically by analysis of variance (ANOVA); all calculations were performed in STATISTICA® 10.0 software (StatSoft, Tulsa, Oklahoma, USA). The basic parameters of statistically homogeneous groups were determined by Tukey's test at $\alpha = 0.05$. The relationships between grain yield and infection index (%) for leaf and stem-base diseases were determined by linear regression analysis. Coefficients of linear correlation (Pearson's r) were calculated.

The wet and warm autumn (October and November) of 2012 and temperature fluctuations from December to March contributed to plant damage and stem-base infections. Mean monthly temperatures in the period from April to August in the growing seasons of 2012 and 2013 were comparable to the long-term average, except for the colder June of 2012. Total precipitation in the analyzed months of 2012 exceeded the norm, and rainfall in excess of 100 mm was noted in June and July. The prevalent weather conditions in the growing season of 2012 promoted the spread of fungal diseases on leaves. In 2013, total precipitation was comparable with the long-term average, and July was the wettest month (Table 2). Temperature was measured with a mercury thermometer placed in an instrument shelter 2 m above the ground. Precipitation was measured with the manual Hellmann rain gauge (Lambrecht 1500). Temperature data were recorded three times a day, at 7.00 a.m., 1.00 p.m. and 7.00 p.m., and average values were calculated for ten-day periods.

Table 2 Weather conditions—data provided by the Meteorological Station in Tomaszkowo (2011–2013)

Growing season	10 days	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII
Mean temperature (°C)													
2011/2012	I	18.2	14.4	12.6	4.8	2.9	2.2	–16.7	–0.4	2.2	13.1	12.2	21.6
	II	16.9	14.6	6.3	0.8	2.4	–6.3	–5.2	4.0	7.2	12.0	16.5	15.5
	III	17.7	13.4	6.2	3.7	1.7	–0.6	1.1	5.3	14.1	14.8	16.4	19.9
	x	17.6	14.1	8.3	3.1	2.3	–1.7	–7.5	3.0	7.8	13.4	15.0	19.0
2012/2013	I	18.6	14.7	10.0	6.1	–3.4	0.8	–0.3	0.2	–0.4	14.7	16.3	18.2
	II	17.0	14.1	8.2	3.8	–4.7	–7.1	–2.1	–6.7	8.7	15.8	18.2	16.6
	III	17.4	11.5	4.4	4.7	–2.4	–7.2	–0.9	–4.0	9.6	13.8	18.1	19.1
	x	17.7	13.5	7.4	4.9	–3.5	–4.6	–1.1	–3.5	5.9	14.8	17.5	18.0
1981–2010	x	17.9	12.8	8.0	2.9	–0.9	–2.4	–1.7	1.8	7.7	13.5	16.1	18.7
Total rainfall (mm)													
2011/2012	I	20.4	24.5	7.6	0	5.9	32.4	0.4	4.6	20.5	0.8	33.8	76.7
	II	44.9	43.0	21.1	8.1	10.3	18.7	6.3	5.9	32.2	48.6	18.5	32.1
	III	16.8	0	0.8	6.0	9.6	10.7	21.0	14.2	20.4	2.3	50.9	12.2
	∑	82.1	67.5	29.5	14.1	25.8	61.8	27.7	24.7	73.1	51.7	103.2	121
2012/2013	I	29.2	2.2	46.4	18.7	0	18.5	14.2	1.9	14.1	6.5	26.4	16.9
	II	9.5	34.1	18.6	1.2	10.2	6.3	8.4	7.4	9.6	20.5	0	100.9
	III	6.4	9.4	3.5	25.3	1.6	19.3	0	8.8	4.8	27.5	34.8	4.1
	∑	45.1	45.7	68.5	45.2	11.8	44.1	22.6	18.1	28.5	54.5	61.2	121.9
1981–2010	∑	59.4	56.9	42.6	44.8	38.2	36.4	24.2	32.9	33.3	58.5	80.4	74.2

Results and Discussion

Severity of Leaf Diseases in Winter Triticale and Rye

The increase in the area under cereal crops, including triticale, in Poland and in other countries around the world has increased the prevalence of crop diseases. According to Nieróbca (2011) and Panasiewicz et al. (2012), weather conditions considerably influence the severity of fungal diseases in winter triticale. Warm May and June as well as rainfall were conducive to the development of *P. recondita.* Panasiewicz et al. (2012) demonstrated that the rate of flag leaf infection by *P. recondita* increased whereas the rate of infection by *R. secalis* decreased in response to sprinkling irrigation. Triticale is a new host species for powdery mildew (*Blumeria graminis*)—in Germany, triticale infections had not been reported before 2001 (Klocke et al. 2013). In the present study, symptoms of powdery mildew on winter triticale and winter rye were noted only in the growing season of 2013 (Fig. 1a and 2a). In initial stages of progression, the disease was observed in both cereal species in May and June under exposure to moderate precipitation and temperatures higher than the long-term average. In July, the spread of powdery mildew was probably inhibited due to high precipitation and below-average temperatures. Symptoms of disease were intensified on triticale leaves in NPK + Zn, NPK + Mn, NPK + Cu + Zn + Mn and NPK + Nano-Gro treatments (infection index ranged from 6 to 8%). The differences in the mean values of the infection index between treatments were not statistically significant. In winter rye, disease symptoms were more severe in treatments with NPK fertilization, foliar fertilization with micronutrients, and the Nano-Gro growth stimulator than in the absolute control treatment. The severity of disease was approximately 19% higher in rye plants supplied with foliar-applied Zn and Mn (Fig. 2a). According to Oborn et al. (2003), balanced plant nutrition increases the availability of selected nutrients and enhances plant disease resistance. Datnoff et al. (2007) observed a higher incidence of *B. graminis* infections in triticale fertilized intensively with N and Zn than in treatments fertilized with K, S and Mn. The growing season of 2012, which was characterized by high precipitation in June and July, below-average temperatures in June and average temperatures in July, was more conducive to the development of the triticale leaf pathogen *Zymoseptoria tritici* than the growing season of 2013. The differences in the mean values between experimental years were statistically significant. In both years of the study, the severity of Septoria leaf blotch was higher in all experimental treatments than in the absolute control treatment, and the only exception was noted in the first year of the study (NPK + Zn) (Fig. 1b) when the highest infection index, above 57%, was observed in the NPK + Cu treatment. In the growing season of 2013, the severity of STB was significantly higher in plants fertilized with NPK and Zn relative to absolute control. According to Solomon et al. (2006), *Z. tritici* is a dangerous pathogen of triticale as well as *Triticum aestivum* and *Triticum durum*. Kurowski et al. (2010) observed that soil fertilization with nitrogen increased the severity of Septoria leaf blotch and brown rust. Foliar application of nitrogen in the form of urea reduced infection rates. Brown rust caused by the fungus *Puccinia recondita* f.sp. *tritici* also poses a significant threat for triticale (Filoda 2009). In the first year of the study, the severity of brown rust symptoms varied significantly from 19.3% (NPK + Nano-Gro) to 29.4% (control-NPK and NPK + Mn) (Fig. 1c). In 2013, fertilization and the Nano-Gro growth

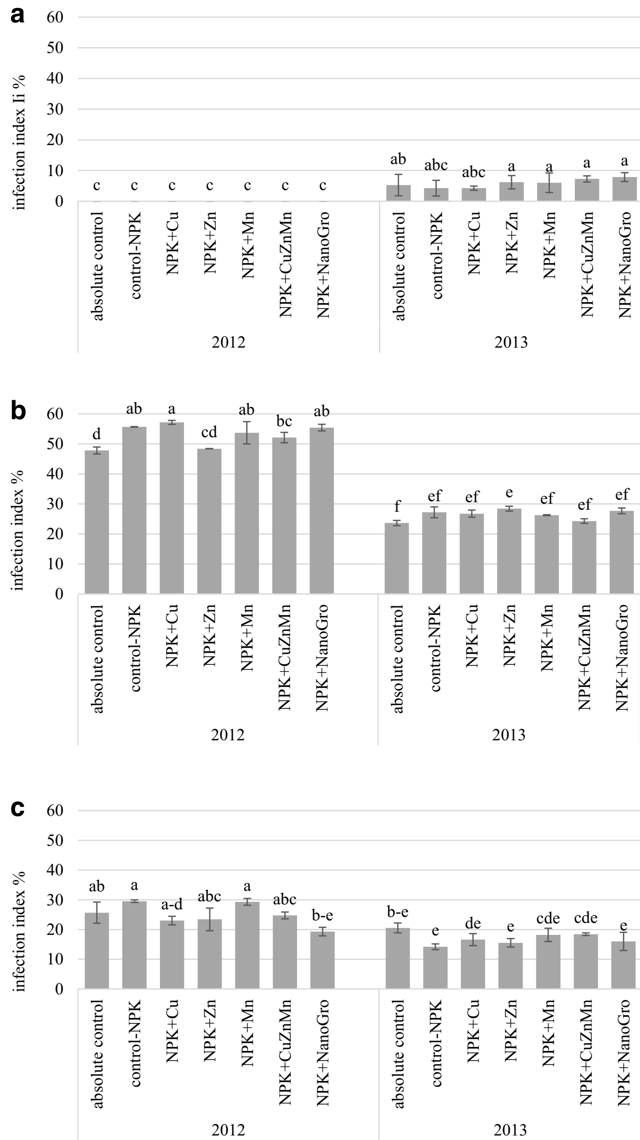

Fig. 1 Symptoms of diseases on winter triticale leaves. **a** Powdery mildew (*Blumeria graminis*). **b** Septoria leaf blotch (*Zymoseptoria tritici*). **c** Brown rust (*Puccinia recondita* f.sp. *tritici*)

stimulator reduced the incidence of brown rust (but not the incidence of Septoria leaf blotch). The differences in infection rates between the experimental treatments and the absolute control treatment were not statistically significant. According to Dordas (2008), above-optimal rates of N fertilizers increase the severity of infections caused by obligate parasites, including pathogens of the genus *Puccinia*. Panasiewicz et al. (2012) observed increased severity of infections caused by *P. recondita, Pyrenophora tritici-repentis, B. graminis* and *Rhynchosporium secalis* in winter triticale fertilized with nitrogen at 60, 120 and 180 kg ha^{-1}. Bhaduri et al. (2014) found a positive correlation between K and Ca concentrations in plant tissues and resistance to fungal diseases.

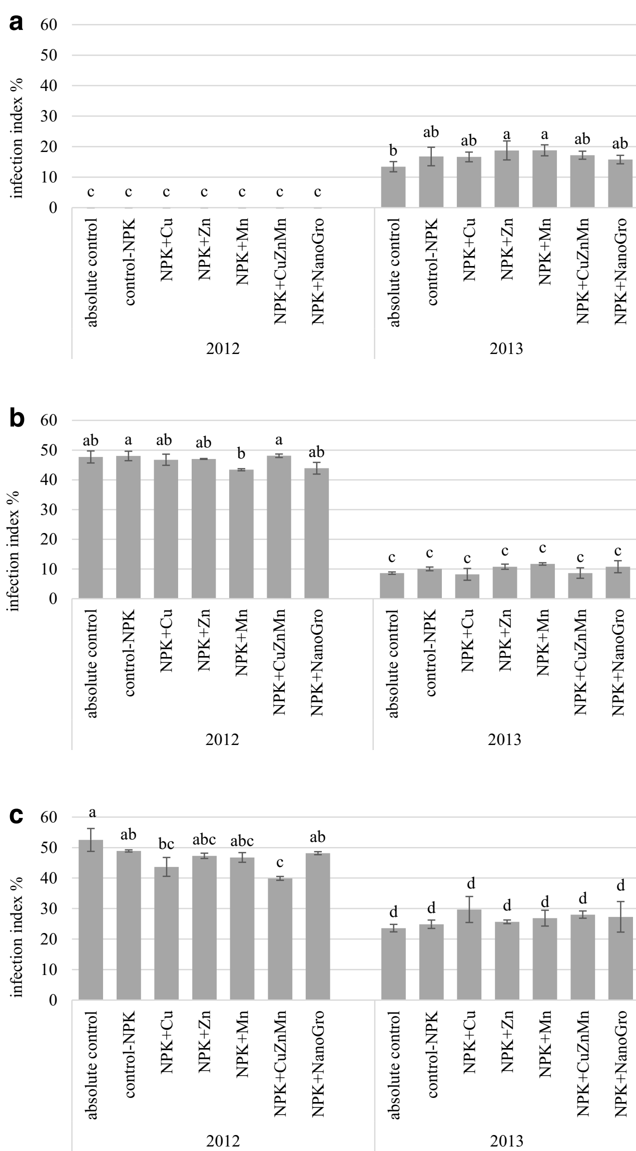

Fig. 2 Symptoms of diseases on winter rye leaves. **a** Powdery mildew (*Blumeria graminis*). **b** Scald (*Rhynchosporium secalis*). **c** Brown rust (*Puccinia recondita* f.sp. *recondita*)

In 2012, symptoms of scald and brown rust were most frequently observed on the leaves of winter rye, and average infection rates during the growing season reached 47% (Fig. 2b, c). The highest severity of infection caused by *Rhynchosporium secalis* was noted in control-NPK and NPK + Cu + Zn + Mn treatments which differed significantly from the least infected plants in the NPK + Mn treatment. The values of infection index were 4-fold or even 5-fold lower in the corresponding treatments in 2013, and the differences between those treatments in the second year of the study were not statistically significant. In 2013, the average infection rate was 4-fold lower in comparison with the previous year (Fig. 2b). Szempliński and Dubis (2005) found that *R. secalis* was responsible for minor losses in rye grain yield in Poland. Lebedeva and Tvarůžek (2006) reported on the pathogenic specialization of *R. secalis* and observed that pathogenic isolates from rye did not infect triticale. In rye plants, the severity of brown rust symptoms was significantly higher in 2012 than in 2013. Winter rye leaves were less severely infected by *Puccinia recondita* f.sp. *recondita* in the NPK + Cu + Zn + Mn treatment than in other treatments in 2012. Significant differences in infection rates were noted between the absolute control treatment (52.5%) vs. the NPK + Cu treatment (43.7%) and the NPK + Cu + Zn + Mn treatment (around 40%). In contrast, in 2013, disease symptoms were intensified under the influence of NPK and the growth stimulator. Significant differences were not observed between treatments, and the infection index ranged from 23.6% in the absolute control treatment to 28% in plants fertilized with NPK + Cu + Zn + Mn (Fig. 2c). Miedaner et al. (2012) demonstrated that brown rust is one of the most prevalent diseases of winter rye in Central-Eastern Europe. The magnitude of production losses is determined mainly by the onset of infection with early infections causing the greatest losses in yield (Bankina et al. 2013). Micronutrients play an important role in the induction and maintenance of plant resistance to pathogens by participating in the formation of biophysical and biochemical barriers (cell wall structure, lignification, increased osmotic pressure in cells, activation of metabolic processes in plants) (Katan 2009). In the present study, in 2012 the lowest values of infection index were recorded for *Z. tritici* in the NPK + Zn treatment on winter triticale leaves, for *R. secalis* in the NPK + Mn treatment and for *P. recondita* in the NPK + Cu + Zn + Mn treatment on winter rye leaves.

Severity of Stem-base Diseases in Winter Triticale and Rye

Stem-base diseases of winter triticale and winter rye were most frequently caused by *Tapesia* spp. and *Fusarium* spp., and only sporadically by *Rhizoctonia* spp. The severity of

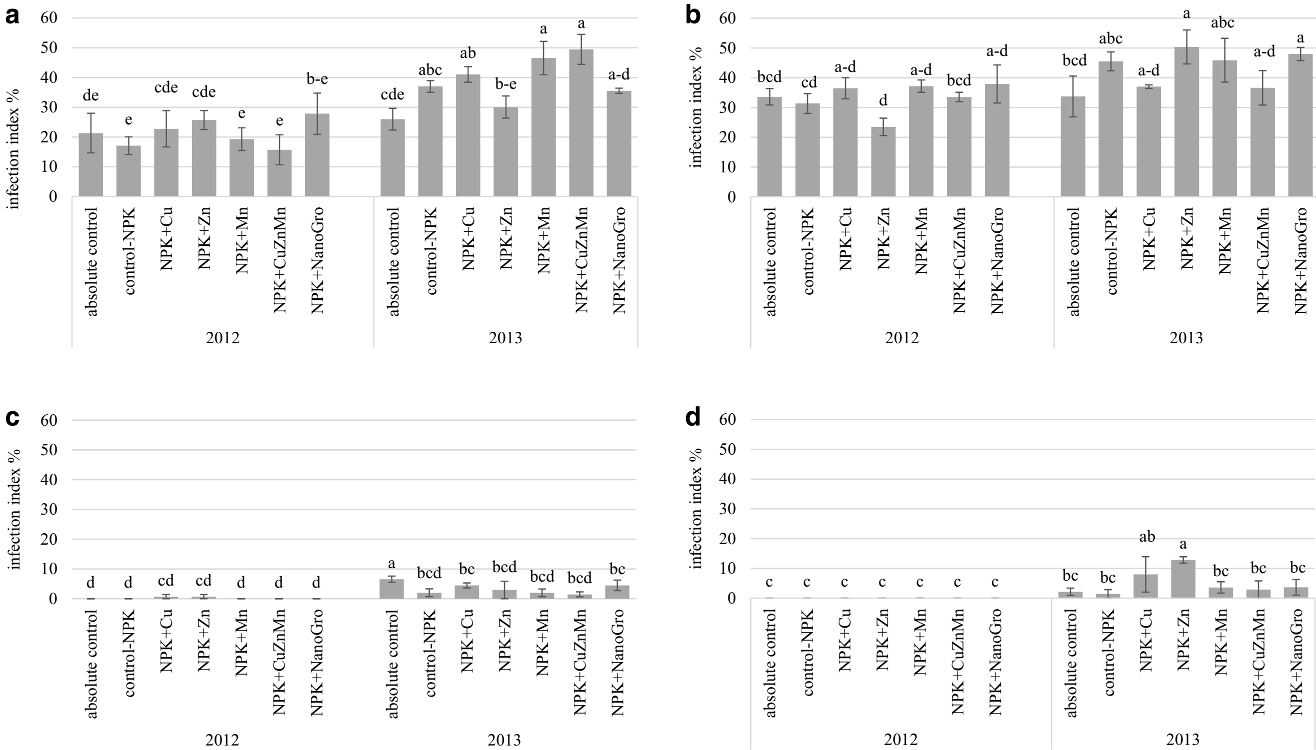

Fig. 3 Symptoms of diseases on winter triticale stem-bases. **a** Eyespot (*Tapesia* spp.). **b** Fusarium foot and root rot (*Fusarium* spp.). **c** Sharp eyespot (*Rhizoctonia* spp.). **d** take-all (*Gaeumannomyces graminis*)

the analyzed diseases was lower in rye than in triticale. Symptoms of eyespot and Fusarium foot and root rot were clearly noted in winter triticale (Fig. 3a, b). Both diseases were more severe in 2013 than in 2012. In the growing season of 2013, their severity was higher in all experimental treatments. The infection index was significantly higher in NPK + Mn and NPK + Cu + Zn + Mn treatments (*Tapesia* spp.) and in the NPK + Zn treatment (*Fusarium* spp.) than in absolute control plants. The influence of mineral fertilization and the Nano-Gro growth stimulator on the severity of both diseases varied in the first year of the study. The severity of eyespot symptoms in winter wheat increased with increasing rates of N fertilizer applied in spring (Huber and Haneklaus 2007). Kurowski et al. (2010) reported higher rates of infections caused by *Fusarium* spp. and *Tapesia yallundae* on the stem bases of triticale fertilized with N applied to soil in three doses than in unfertilized plants. Supplemental foliar fertilization with urea (replacing one soil application of N) inhibited the spread of diseases.

In this study, the severity of eyespot symptoms in rye decreased in the first growing season in treatments with fertilizers and the growth stimulator relative to absolute control, but the differences between treatments were not significant (Fig. 4a). In 2013, the rates of infection caused by *Tapesia* spp. were significantly higher than in 2012. The severity of disease symptoms was higher in treatments fertilized with NPK + Zn, NPK + Mn, NPK + Cu + Zu + Mn and NPK + Nano-Gro. In both years of the study, NPK fertilization, foliar application of micronutrients and the growth stimulator exerted varied effects on the severity of Fusarium foot and root rot on winter rye (Fig. 4b). In 2012, the severity of infections caused by *Fusarium* spp. was highest in the NPK + Cu treatment (37.3%), and it differed significantly from all treatments in 2012, and from the NPK + Zn and NPK + Mn treatment (about 23%) in 2013. The average values of the infection index did not differ significantly between experimental years. Mielniczuk et al. (2012) observed significant variations in the severity of root and stem-base diseases manifested by necrosis in winter rye (7.5–46.7%). According to the cited authors, the noted infections were caused mainly by *Fusarium* spp. Katan (2009) demonstrated that mineral fertilization stimulates soil microbial activity and reduces the occurrence of pathogens responsible for take-all disease. High rates of N fertilization reduce the severity of infections caused by *Fusarium* spp. (Dordas 2008). Bhaduri et al. (2014) observed that the incidence of root and stem-base diseases, including infections caused by *Fusarium* spp. and *Rhizoctonia* spp., can be effectively minimized only through the use of nitrates, whereas fertilizers containing nitrogen as ammonium deliver the opposite effect.

In our study, sharp eyespot was noted sporadically in winter triticale in 2012, and it was observed only in treatments with foliar-applied Cu and Zn (Fig. 3c). In 2013, the

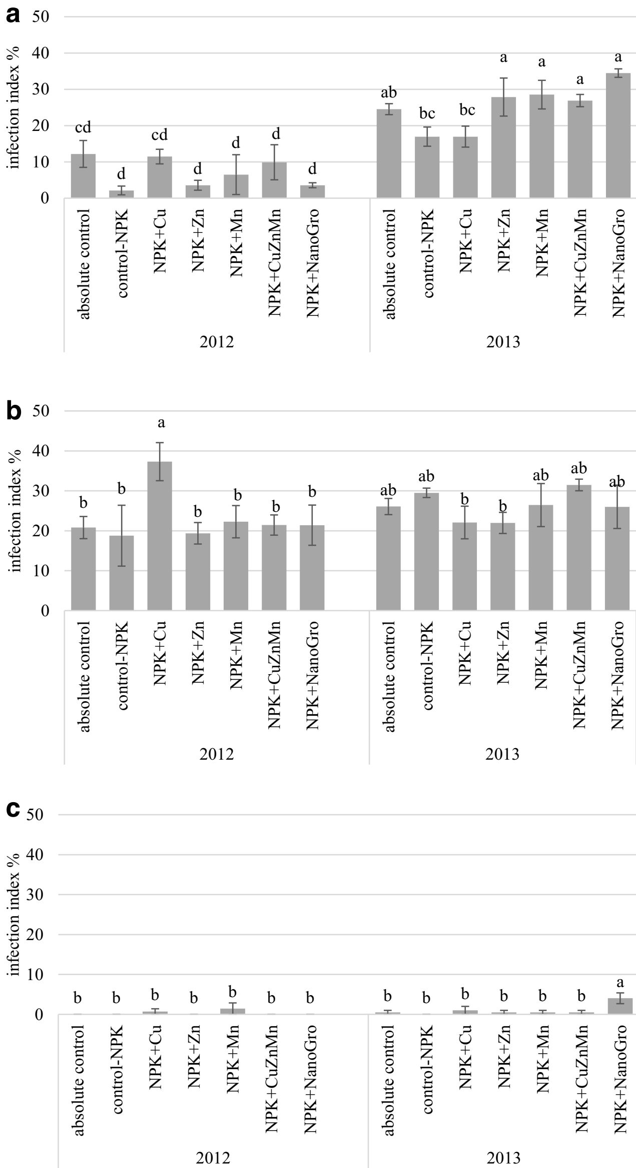

Fig. 4 Symptoms of diseases on winter rye stem-bases. **a** Eyespot (*Tapesia* spp.). **b** Fusarium foot and root rot (*Fusarium* spp.). **c** Sharp eyespot (*Rhizoctonia* spp.)

severity of infections caused by *Rhizoctonia* spp. decreased significantly in plants fertilized with NPK + Nano-Gro relative to absolute control. In both years of the study, the above disease was observed sporadically in rye, and the highest infection rate (at only 4%) was noted in the treatment with the Nano-Gro growth stimulator in 2013 (Fig. 4c). The higher incidence of sharp eyespot, observed on the stem-bases of both cereal species in the growing season of 2013, could be due to the warm and wet autumn of 2012. According to Bockus et al. (2010), the above weather conditions in autumn combined with cold and wet spring contribute to infections and tissue colonization by the pathogen. Previous research (Huber and Haneklaus 2007) has shown that the severity of eyespot symptoms increased when N was applied in a cold and wet period, when wheat seeds were still dormant, and weather conditions promoted the spread of disease. Pre-sowing application of zinc fertilizer or manure with high Zn content reduced the prevalence of eyespot caused by *Rhizoctonia cerealis*. Research Lemańczyk (2012) revealed that lower rates of N fertilization did not reduce the severity of infections of winter triticale caused by *Rhizoctonia.*

In the present study, symptoms of infection caused by *Gaeumannomyces graminis* were observed only on triticale stem bases in 2013. The highest infection index (12.8%) was noted in the NPK + Zn treatment, and it differed significantly from the values recorded in the remaining treatments (excluding NPK + Cu) (Fig. 3d). Magnesium participates in the synthesis of lignins and suberins (Vidhyasekaran 2004), and according to Krauss (1999), those compounds induce resistance to *G. graminis* in wheat. According to Thompson and Huber (2006), nitrogen applied as ammonium was more effective than nitrate in inducing resistance to pathogens and enhancing the activity of micronutrients, including Mn which has a toxic effect on selected pathogens.

According to the above authors, soil-dwelling microorganisms can promote or inhibit disease development because they affect nutrient bioavailability. In the cited study, virulent isolates of *G. graminis* contributed to manganese oxidation in soil, at the site of infection, and oxidized Mn is unavailable to plants. Since Mn participates in physiological

Table 3 Grain yield of triticale and rye (t ha^{-1})

	Winter triticale			Winter rye		
	2012	2013	x	2012	2013	x
Absolute control	5.3 b	8.1 a	6.7 A	6.7 d	7.3 cd	7.0 B
Control-NPK	5.8 b	8.5 a	7.2 A	9.6 a	7.4 bcd	8.5 A
NPK + Cu	5.6 b	8.7 a	7.2 A	8.4 abc	7.7 bcd	8.1 A
NPK + Zn	6.0 b	8.5 a	7.2 A	8.7 ab	7.3 cd	8.0 A
NPK + Mn	5.9 b	8.7 a	7.3 A	9.2 a	7.3 cd	8.2 A
NPK + Cu + Zn + Mn	5.5 b	8.2 a	6.9 A	8.5 abc	7.8 bcd	8.1 A
NPK + Nano-Gro	5.5 b	8.5 a	7.0 A	8.3 abc	7.3 cd	7.8 AB
X	5.7 N	8.4 M	–	8.5 M	7.4 N	–

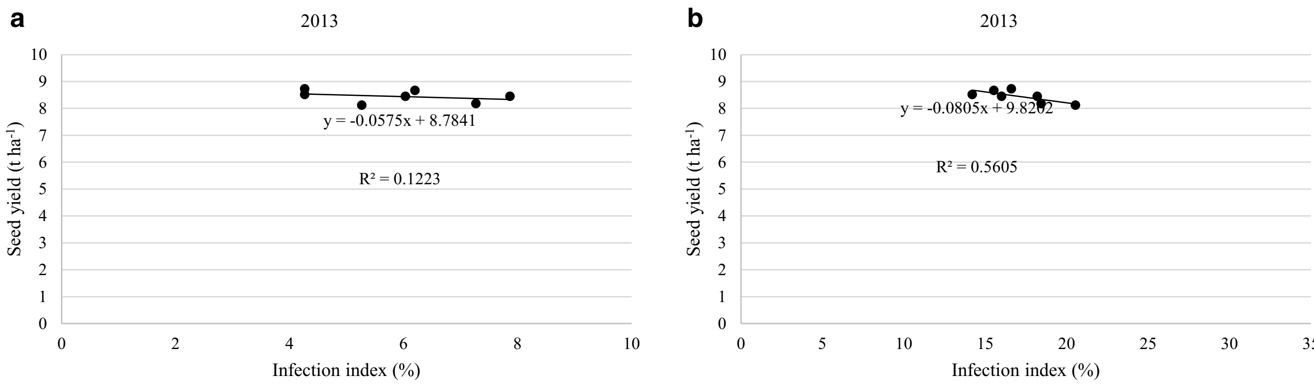

Fig. 5 Correlations between grain yield and the severity of leaf diseases in winter triticale. **a** *Blumeria graminis*. **b** *Puccinia recondite*

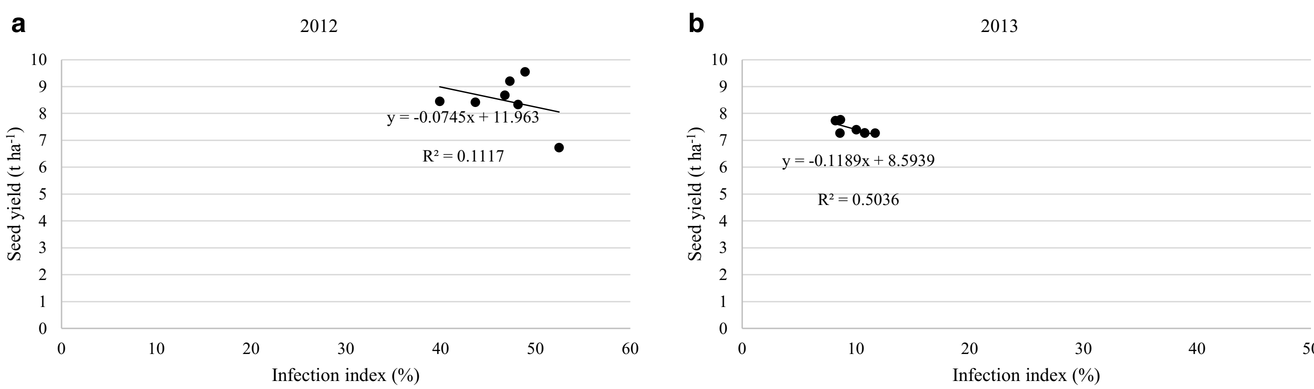

Fig. 6 Correlations between grain yield and the severity of leaf diseases in winter rye. **a** *Puccinia reconditea.* **b** *Rhynchosporium secalis*

and biochemical processes in plants, local Mn deficiencies can reduce plant resistance to pathogens.

Yield of Winter Triticale and Rye

Triticale grain yield was higher in 2013 than in 2012 (Table 3). However, the increase in grain yield in response to mineral fertilization and the growth stimulator was not statistically significant—in 2012, the highest increase of 13.2% was noted in the NPK + Zn treatment, and in 2013, the highest increase of 7.4% was observed in NPK + Cu and NPK + Mn treatments relative to absolute control. Rye responded positively to fertilization and the growth stimulator in the first year of the study, and grain yield increased by 37.3–43.3% (NPK + Mn and control-NPK). In 2013, a non-significant increase in grain yield was noted in selected experimental treatments relative to absolute control. In a study by Stępień et al. (2016), an average increase in rye yields over two years reached 0.98–1.48 t ha^{-1} in the control-NPK and NPK with microelements and Nano-Gro® treatments, compared with the absolute control treatment. High rates of N fertilization at 120 kg ha^{-1} (Sekeroglu and Yilmaz 2001) or even 150–180 kg ha^{-1} (Mut et al. 2005) were found to increase triticale grain yield. Recent research (Saglam and Ustunalp 2014) also demonstrated that higher N rates increase triticale yield. Balanced NPK + Mg fertilization and the introduction of new cultivars contributed to a gradual increase in the yield of winter rye in a long-term experiment (Jate 2010). Bameri et al. (2012) demonstrated that micronutrient fertilizers have a beneficial influence on cereal production. Cereal yield is reduced by zinc deficiency (Alloway 2009). In a study by László (2008), triticale yield was highest when Mn concentrations in soil were in the range of 0.0287–0.0296 g Mn^{++} kg^{-1}. The foliar fertilizers applied in the study, containing boron, phospho-

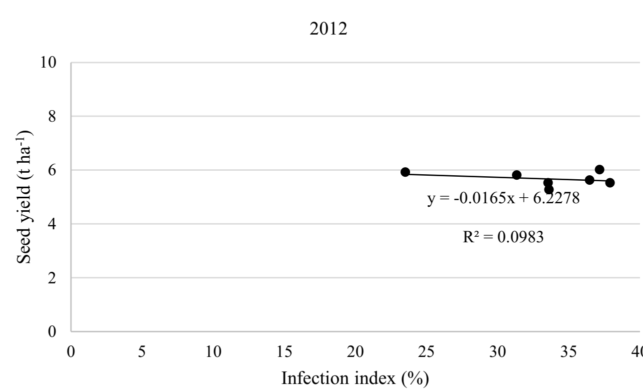

Fig. 7 Correlations between grain yield and the severity of stem-base diseases in winter triticale (*Fusarium* spp.)

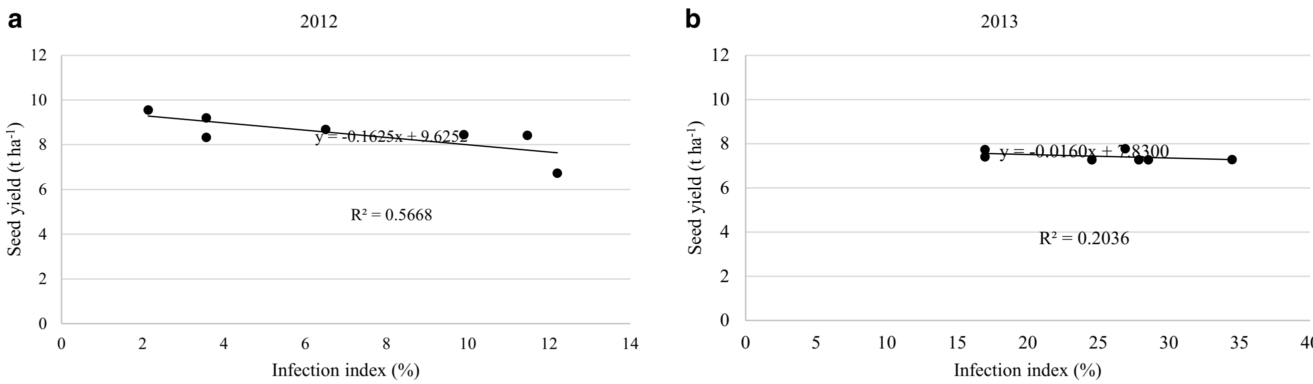

Fig. 8 Correlations between grain yield and the severity of stem-base diseases in winter rye (*Tapesia* spp.). **a** 2012. **b** 2013

rus and potassium (FoliCare), and nitrogen and magnesium with micronutrients (B, Cu, Fe, Mn, Mo and Zn—Insol 3) had no significant effect on the grain yield of winter triticale (Kwiecińska-Poppe et al. 2010).

Coefficients of Correlation (Pearson's r)

In this study, grain yield was influenced by the severity of diseases (presented as the infection index in %). The calculated coefficients of correlation (Pearson's *r*) revealed a drop in grain yield when winter triticale leaves were infected by *Blumeria graminis* (r = –0.3498) and *Puccinia recondita* f.sp. *tritici* (r = –0.7487) in 2013, and when winter rye leaves were infected by *P. recondita* f.sp. *recondita* in 2012 (r = –0.3342) and by *Rhynchosporium secalis* in 2013 (r = –0.7096) (Figs. 5 and 6).

A reduction in yield was also noted with an increase in the incidence of stem-base diseases caused by *Fusarium* spp. in triticale in 2012 (r = –0.3136) and by *Tapesia* spp. in winter rye in both years of the study (r = –0.7529 and r = –0.4512, respectively) (Figs. 7 and 8). The observed correlations were validated in a regression analysis. Balanced N and K fertilization determines plant resistance to pathogens. Potassium fertilization reduces the severity of selected cereal diseases and increases yield (Sharma et al. 2005). Witkowska et al. (2011) found a highly significant positive correlation between resistance to *Stagonospora nodorum* and the grain yield of winter wheat.

Conclusion

Weather conditions in the growing seasons of 2012 and 2013 influenced the severity of diseases on winter triticale and winter rye. High levels of precipitation in June 2012 contributed to the development Septoria leaf blotch (*Zymoseptoria tritici*) on triticale and scald (*Rhynchosporium secalis*) on rye, whereas warm May and June with moderate precipitation in 2013 promoted the spread of powdery mildew on the leaves of both cereal species. The results of this study suggest that the severity of most cereal diseases can be minimized through the application of macronutrient and micronutrient fertilizers. The use of NPK fertilizers, foliar micronutrient fertilizers and the Nano-Gro growth stimulator reduced the severity of brown rust (expressed as the infection index in %) on rye in 2012 and on triticale in 2013, eyespot on rye in 2012, and sharp eyespot on triticale in 2013. In the present study, fertilization with micronutrients Cu, Zn and Mn exerted varied effects on the severity of leaf and stem-base diseases on triticale and rye. However, in 2012 the lowest values of the infection index were recorded for *Z. tritici* in the NPK + Zn treatment on winter triticale leaves, for *R. cerealis* in the NPK + Mn treatment and for *P. recondita* in the NPK + Cu + Zn + Mn treatment on winter rye leaves, and for *Fusarium* spp. in the NPK + Zn treatment on winter triticale stem-bases. In both years of the study, triticale and rye responded positively to mineral fertilization and the growth stimulator. A negative correlation was observed between the severity of selected diseases on triticale and rye (triticale: *Blumeria graminis* and *Puccinia recondita* f.sp. *tritici* in 2013, *Fusarium* spp. in 2012; rye: *P. recondita*. f. sp. *recondita* in 2012, *Rhynchosporium secalis* in 2013, and *Tapesia* spp. in both years of the study) and grain yield.

Conflict of interest B. Cwalina-Ambroziak, M. Głosek-Sobieraj, M. Damszel and A. Stępień declare that they have no competing interests.

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