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ORIGINAL PAPER

EVALUATION OF THE EFFECT OF DIFFERENT LEVELS OF NITROGEN AND MANGANESE FERTILISER ON THE YIELD, MACRONUTRIENT CONTENT AND TECHNOLOGICAL PROPERTIES OF WINTER WHEAT*

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Abstract

The management of nutrients in wheat cultivation should take into account the demand for N and other nutrients. A field experiment involving the cultivation of winter wheat was carried out in the years 2013-2016 at the Educational and Experimental Station of the University of Warmia and Mazury in Tomaszkowo (53°72 N; 20°42 E), Poland. The aim of the study was to assess the effects of fertilisation with two nitrogen doses (150 and 200 kg ha^{-1}) and three manganese doses (0.5, 1.0 and 1.5 kg ha^{-1}) on yield components, crop productivity, macronutrient content and technological indicators for grain (protein, gluten and starch contents, Zeleny sedimentation index, hardness and bulk density of grains). Nitrogen fertilisation (150 and 200 kg ha^{-1}) and foliar Mn spraying (0.5, 1.0 and 1.5 kg ha^{-1}) had no clear effect on grain yields, technological quality indicators, selected biometric features or the yield components, and the expected results were distorted by the changeable weather conditions. On average, regardless of Mn application, a higher nitrogen dose increased the protein and gluten content as well as the Zeleny index value in the first and the second year of the study. Under the influence of the higher N dose, the Ca content of grains increased; however, it was only statistically confirmed in the first and third year of the study. An increase in nitrogen fertilisation in variants with different Mn doses and without its application promoted an increase in the protein and gluten content, yet it was only statistically confirmed in the first year of the study. An increase in nitrogen fertilisation from 150 to 200 kg ha^{-1} as well as additional Mn spraying did not significantly differentiate the P, K and Mg content of wheat grains.

Keywords: foliar fertilisation, manganese fertilisation, grain quality, macronutrients.

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INTRODUCTION

Satisfying the nutritional needs of plants is the crucial factor determining the productivity and quality of plants (Karim et al. 2012, Hellemans et al. 2018). The management of nutrients in the cultivation of wheat should take into account the demand for N as well as for other nutrients (Dimkpa, Bindraban 2016, Rietra et al. 2017). In practice, of all the nutrients essential for plants, N, P, K and Ca (López-Arredondo et al. 2013, Gaj, Górski 2014) are the elements that are removed with harvested crops in large quantities and require annual supplementation. Large quantities of nitrogen are mainly needed by plants during the rapid growth phase. Given the possibility of nitrogen accumulation by a plant, where the nitrogen concentration in the soil is high, the absorption of this element is much more rapid that the growth of plants (Hamnér et al. 2017). Nitrogen is a factor determining the technological properties of grains (total protein and wet gluten content as well as other parameters) (Harasim, Wesołowski 2013). In order to produce high and stable yields of wheat, is it necessary to apply yield-stimulating macronutrients and to ensure sufficient availability of micronutrients (Rietra et al. 2017). Microelements, their mutual interactions and physiological links with macronutrients affect physiological processes of plants, which is reflected by the productivity and quality of grains (Zeidan et al. 2010, Knapowski et al. 2016, Stępień, Wojtkowiak 2016).

Micronutrients which are most frequently listed as necessary in feeding cereal plants include copper, zinc and manganese. The latter participates in crucial physiological processes occurring in a plant (Sieprawska et al. 2016). Plants with Mn deficiency exhibit reduced growth and, consequently, produce lower yield; they are also more susceptible to pathogens and damage under extreme conditions (Socha, Guerinot 2014). Manganese stimulates the uptake of phosphorus and therefore indirectly contributes to the development of the root system (Pedas et al. 2011).

A practical way of providing plants with micronutrients is to apply them to the leaves, alternatively in a mixture with urea. The foliar application results in the rapid absorption through the plants' leaf cuticle, which ensures an almost instantaneous access to other parts of plants through the xylem and phloem (Haslett et al. 2001). The integration of macronutrient fertilisation with micronutrient fertilisation improves the technological properties of grains/flour as well as the nutritional quality (Knapowski et al. 2016).

The aim of the study was to assess the effects of fertilisation with two nitrogen doses and three manganese doses on yield components, crop productivity, macronutrient content, and technological indicators for grain (protein, gluten and starch content, Zeleny sedimentation index, hardness and bulk density of grains).

MATERIALS AND METHODS

The field experiment was carried out in the years 2013-2016 at the Educational and Experimental Station of the University of Warmia and Mazury in Tomaszkowo (53°72 N; 20°42 E), Poland. Winter wheat (*Triticum aestivum* L.) was cultivated on lessive soil with the textural composition of silty clay loam, complex 4, class IIIb in the Polish soil valuation system. According to the World Reference Base for Soil Resources (WRB, 2014), this corresponds to Haplic Cambisol. The soil's reaction was slightly acidic (pH of 5.7 in KCl), carbon content was 10.1 g kg^{-1}, and total nitrogen content was 0.97 g kg^{-1}. Soil richness in assimilable nutrients was high for P (83.3 mg kg^{-1}), and medium for K (145.3 mg kg^{-1}), Mg (68.7 mg kg^{-1}) and Mn (150 mg kg^{-1}). The concentrations of soil nutrients were adequate according to the valid standards and standard methods applied in Poland. The experiment was carried out in the random block design with three replications. The area of a plot was 9.90 m^2; the area of a plot for harvesting was 8.00 m^2. Winter wheat of the variety Sailor was sown after winter triticale, at a density of 550 grains m^{-2}, in rows spaced at 12 cm apart.

The study factors included fertilisation of wheat with nitrogen in two doses (150 and 200 kg ha^{-1}) and the foliar application of manganese in three doses (0.5, 1.0 and 1.5 kg ha^{-1}).

Nutrient dose levels and the times of their application are provided in Table 1. Manganese was applied to the leaves during the stem elongation phase /BBCH 30-31/ in the form of a 0.5% solution of $MnSO_4 \cdot 5H_2O$.

Prior to sowing, 70 kg P ha^{-1} (triple superphosphate with P content of 20%) and 100 kg K ha^{-1} (a potassium salt with K content of 46%) were applied.

The sowing, cultivation measures and the harvest of wheat were conducted in accordance with the agrotechnical requirements specific to a particular plant species. Weeds were controlled using herbicides. No protection against pests or diseases was applied.

Table1

Doses of N fertilisation

Time of application/Growth stages (BBCH)		Pre-sowing	Tillering/ BBCH 25-29	Stem elongation/ BBCH 30-31	Heading/ BBCH 51–52
Type of fertilizer		urea 46% ($CO(NH_2)_2$)	ammonium nitrate 34% (NH_4NO_3)	ammonium nitrate 34% (NH_4NO_3)	urea 46% ($CO(NH_2)_2$), foliar application of a 10% solution
Sum of N fertilisation (kg ha^{-1})	150	40	70	30	10
	200	40	80	60	20

Wheat grain yields were determined at the moisture content of 15%. The grains were fractionated using Vogel's screens; those smaller than 2.0 mm were classified as screenings. The weight of a thousand grains was determined using an LN-S, 50A seed counter (Unitra, Szczytno, Poland). Ground grain samples were mineralised in H_2SO_4 with the addition of H_2O_2 as an oxidising agent. The P content was determined by the vanadium and molybdenum method, the K and Ca content was assessed by atomic emission spectrometry (AES) and the Mg content was measured by atomic absorption spectroscopy (AAS) – PANAK (1997).

Using 1.0 kg grain samples, the content of proteins, wet gluten, starch, the Zeleny sedimentation index, grain hardness and bulk density of grains were determined using a NIR System Infratec 1241 Analyzer (Foss, Hillerod, Denmark).

Meteorological conditions during the growing periods of winter wheat, particularly in the spring and summer months, which determine the yield of grains, yield components and its quality, were varied, especially in terms of the amount of precipitation in particular years (Table 2). Total precipitation during the rapid growth phase (April to July), depending on the year, was 146.8-285.4 mm, with the average multi-annual value of 246.4 mm. Total monthly precipitation levels, significantly lower than the multi-annual average values, were noted in 2014 from April to August. Precipitation deficits were noted in the spring and summer season (from May to June 2015). The average monthly air temperature from April to July was from 12.9°C in 2015, 14.1°C in 2016, to 14.2°C in 2014, compared to the average multi-annual temp. of 14.0°C.

The results were statistically processed in Statistica 13.0 software (StatSoft, Tulsa, Oklahoma, USA) using two-way ANOVA. Basic parameters and homogeneous groups were determined by the Tukey's test at $P \leq 0.05$

RESULTS AND DISSCUSSION

The yield of winter wheat of the variety Sailor, cultivated in the years 2013-2016, ranged from 2.62 to 11.80 Mg ha^{-1}, and was not determined by the course of weather conditions rather than the experimental factors (Table 3). The effect of the amount of precipitation and temperature distribution on the yield levels has been confirmed by ELLMANN (2011), STĘPIEŃ, WOJTKOWIAK (2016), and WALSH et al. (2018). In our experiment, the highest yields were obtained in the first growing season 2013/2014. The yield of grains in the second year of the study was lower, on average, by approx. 7 Mg ha^{-1}. During that growing season (2014/2015), limited rainfall was noted in February and from late April to late July. Water shortages occurred during the period of the rapid growth of plants. Very low yields produced in the season of 2015/2016 resulted from the very unfavourable course of thermal conditions during the winter period. Due to high temperatures in November and

Table 2

Monthly air temperature and rainfall in 2013-2016 season

Temperature	Month												
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	av. Sep - Aug
2013/2014	11.3	8.9	5.0	2.3	-4.0	1.2	5.1	8.8	13.0	14.4	20.4	17.1	8.6
2014/2015	13.6	8.7	3.7	-0.4	0.4	0.5	4.2	6.7	11.8	15.5	17.5	19.8	8.5
2015/2016	13.5	6.1	4.8	3.4	-4.0	2.3	3.0	7.4	13.7	17.1	18.1	17.1	8.5
1981-2010	12.8	8.0	2.9	-0.9	-2.4	-1.7	1.8	7.7	13.5	16.1	18.7	17.9	7.9
Rainfall	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sum Sep - Aug
2013/2014	101.1	16.0	18.0	27.7	48.4	8.1	57.7	26.0	32.7	50.8	37.3	86.1	509.9
2014/2015	25.9	15.1	34.0	61.8	46.8	6.8	45.1	38.2	29.7	29.5	81.9	14.3	429.1
2015/2016	63.8	19.4	84.5	56.6	24.7	57.1	21.6	28.8	56.9	69.3	130.4	70.4	683.5
1981-2010	56.9	42.6	44.8	38.2	36.4	24.2	32.9	33.3	58.5	80.4	74.2	59.4	581.7

Table 3

Grain yield, thousand-kernel weight, content of screenings under different treatments from 2014 to 2016

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				Av. for doses of Mn
		0.0	0.5	1.0	1.5	
Yield of grain (Mg ha^{-1})						
2014	150	11.0*a*	11.3*a*	11.1*a*	11.2*a*	11.2*a*
	200	11.3*a*	11.6*a*	11.4*a*	11.8*a*	11.5*a*
	av. for N	11.1*a*	11.5*a*	11.2*a*	11.5*a*	-
2015	150	6.19*a*	7.08*a*	5.83*a*	5.80*a*	6.23*a*
	200	6.73*a*	6.50*a*	7.27*a*	5.57*a*	6.52*a*
	av. for N	6.46*a*	6.79*a*	6.55*a*	5.68*a*	-
2016	150	2.92*a*	2.99*a*	2.96*a*	2.62*a*	2.87*a*
	200	3.03*a*	2.70*a*	3.45*a*	3.07*a*	3.06*a*
	av. for N	2.97*a*	2.85*a*	3.21*a*	2.85*a*	-
Thousand-kernel weight (g)						
2014	150	43.6*a*	44.1*a*	44.3*a*	44.2*a*	44.0*a*
	200	45.1*a*	44.4*a*	44.0*a*	43.3*a*	44.2*a*
	av. for N	44.3*a*	44.2*a*	44.1*a*	43.8*a*	-
2015	150	43.6*a*	46.1*a*	42.7*a*	42.9*a*	43.8*a*
	200	44.2*a*	44.9*a*	46.5*a*	42.9*a*	44.6*a*
	av. for N	43.9*a*	45.5*a*	44.6*a*	42.9*a*	-
2016	150	42.4*a*	41.9*a*	41.3*a*	40.2*a*	41.7*a*
	200	41.7*a*	42.2*a*	42.1*a*	43.7*a*	42.2*a*
	av. for N	42.0*a*	42.0*a*	41.7*a*	42.0*a*	-

a, *b*, *c*, ... values with the same letter are not significantly different according to the Tukey's test ($P \leq 0.05$)

December, the plants did not stop growing. The sudden drop of temperatures at the beginning of January, combined with the lack of snow cover, resulted in some plants being killed by frost.

Nitrogen fertilisation (150 and 200 kg ha^{-1}) and foliar Mn spraying (0.5, 1.0 and 1.5 kg ha^{-1}) had no effect on selected biometric traits or the yield components (Table 4). Moreover, a study by Ellmann (2011) noted no significant effects of a nitrogen level on these features. An increase in the yield of grains of wheat cultivated using the intensive and integrated technology resulted from a greater number of ears per surface unit, greater weight of 1000 grains and higher number of grains per ear (Podolska, Sułek 2012, Buczek, Bobrecka-Jamro 2015). According to Cossani et al. (2009), a negative response of the weight of grains to nitrogen fertilisation occurred, even though the magnitude of this effect each year differed depending on the

Table 4

Length of spike, number and weight of grain per spike under different treatments from 2014 to 2016

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				Av. for doses of Mn
		0.0	0.5	1.0	1.5	
Length of spike (mm)						
2014	150	65.9*a*	64.4*a*	62.8*a*	64.2*a*	63.9*a*
	200	64.4*a*	67.9*a*	67.0*a*	66.0*a*	66.3*a*
	av. for N	64.2*a*	66.2*a*	64.9*a*	65.1*a*	-
2015	150	74.1*a*	69.8*a*	74.6*a*	72.1*a*	72.6*a*
	200	73.8*a*	68.8*a*	72.7*a*	71.7*a*	71.7*a*
	av. for N	73.9*a*	69.3*a*	73.6*a*	71.9*a*	-
2016	150	84.4*a*	80.5*a*	79.9*a*	82.8*a*	81.9*a*
	200	80.6*a*	80.7*a*	86.6*a*	80.3*a*	82.0*a*
	av. for N	82.5*a*	80.6*a*	83.3*a*	81.5*a*	-
Number of grain per spike						
2014	150	31.7*a*	32.9*a*	35.1*a*	34.4*a*	33.5*a*
	200	32.5*a*	36.6*a*	32.8*a*	36.8*a*	34.7*a*
	av. for N	32.1*a*	34.7*a*	34.0*a*	35.6*a*	-
2015	150	34.3*a*	27.0*a*	33.4*a*	28.3*a*	30.7*a*
	200	31.9*a*	25.1*a*	30.2*a*	29.6*a*	29.2*a*
	av. for N	33.1*a*	26.0*a*	31.8*a*	28.9*a*	-
2016	150	51.1*a*	41.9*a*	48.6*a*	49.9*a*	47.9*a*
	200	47.0*a*	45.0*a*	49.8*a*	46.3*a*	47.0*a*
	av. for N	49.0*a*	43.4*a*	49.2*a*	48.1*a*	-
Weight of grain per spike (g)						
2014	150	1.38*a*	1.34*a*	1.51*a*	1.55*a*	1.45*b*
	200	1.49*a*	1.65*a*	1.45*a*	1.64*a*	1.56*a*
	av. for N	1.44*a*	1.50*a*	1.48*a*	1.60*a*	-
2015	150	1.66*a*	1.17*a*	1.53*a*	1.27*a*	1.41*a*
	200	1.45*a*	1.14*a*	1.42*a*	1.29*a*	1.32*a*
	av. for N	1.55*a*	1.15*a*	1.47*a*	1.28*a*	-
2016	150	2.24*a*	2.08*a*	2.10*a*	2.16*a*	2.14*a*
	200	2.11*a*	2.03*a*	2.15*a*	2.05*a*	2.09*a*
	av. for N	2.17*a*	2.06*a*	2.13*a*	2.11*a*	-

a, *b*, *c*, … values with the same letter are not significantly different according to the Tukey's test ($P \leq 0.05$)

environmental conditions. As reported by KARIM et al. (2012), foliar Mn fertilisation in wheat is only suitable under stress conditions. The yield of grains, yield of straw, weight of a 1000 grains and number of grains per ear were significantly increased through the foliar Mn application to wheat on light soil (ZEIDAN et al. 2010).

The indicators of the technological properties of winter wheat grains are presented in Table 5. Their values, similarly to those for the grain yields, were determined by the course of weather conditions. The grains harvested

Table 5

Content of protein, gluten, starch, Zeleny index, hardness and density of grain under different treatments from 2014 to 2016

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				av. for doses of Mn
		0.0	0.5	1.0	1.5	
Protein (g kg^{-1})						
1	2	3	4	5	6	7
2014	150	97.7*b*	100.7*b*	96.3*b*	99.0*b*	98.4*b*
	200	111.0*a*	109.3*a*	112.3*a*	109.3*a*	110.5*a*
	av. for N	104.3*a*	105.0*a*	104.3*a*	104.2*a*	-
2015	150	120.0*b*	121.7*ab*	123.7*ab*	124.7*ab*	122.5*b*
	200	130.3*ab*	131.0*ab*	126.7*ab*	133.3*a*	130.3*a*
	av. for N	125.2*a*	126.3*a*	125.2*a*	129.0*a*	-
2016	150	149.0*a*	161.0*a*	150.3*a*	149.3*a*	152.4*a*
	200	156.7*a*	163.3*a*	155.3*a*	155.7*a*	157.8*a*
	av. for N	152.8*a*	162.2*a*	152.8*a*	152.5*a*	-
Gluten (g kg^{-1})						
2014	150	203.3*b*	208.0*b*	198.0*b*	205.7*b*	203.8*b*
	200	233.3*a*	232.7*a*	244.7*a*	232.7*a*	235.8*a*
	av. for N	218.3*a*	220.3*a*	221.3*a*	219.2*a*	-
2015	150	258.7*a*	265.3*a*	263.0*a*	267.3*a*	263.6*b*
	200	286.3*a*	286.7*a*	275.0*a*	286.3*a*	283.6*a*
	av. for N	272.5*a*	276.0*a*	269.0*a*	276.8*a*	-
2016	150	325.7*a*	355.0*a*	325.7*a*	321.7*a*	332.0*a*
	200	345.0*a*	362.3*a*	342.0*a*	343.0*a*	348.1*a*
	av. for N	335.3*a*	358.7*a*	333.8*a*	332.3*a*	-
Starch (g kg^{-1})						
2014	150	715.7*a*	730.0*a*	718.7*a*	698.6*a*	715.6*a*
	200	691.0*a*	706.0*a*	693.3*a*	706.0*a*	699.1*a*
	av. for N	703.3*a*	718.0*a*	706.0*a*	702.0*a*	-
2015	150	702.0*a*	704.7*a*	700.0*a*	698.3*a*	701.3*a*
	200	693.3*a*	697.7*a*	699.3*a*	691.3*a*	695.4*a*
	av. for N	697.7*a*	701.2*a*	699.7*a*	694.8*a*	-

cont. Table 5

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				av. for doses of Mn
		0.0	0.5	1.0	1.5	
1	2	3	4	5	6	7
2016	150	659.7*a*	640.3*a*	657.0*a*	658.0*a*	653.8*a*
	200	653.3*a*	639.7*a*	655.3*a*	653.0*a*	650.3*a*
	av. for N	656.5*a*	640.0*a*	656.2*a*	655.5*a*	-
Zeleny index (mL)						
2014	150	21.6*a*	25.0*a*	21.1*a*	20.6*a*	22.0*b*
	200	27.4*a*	27.8*a*	28.2*a*	28.1*a*	27.9*a*
	av. for N	24.5*a*	26.4*a*	24.7*a*	24.3*a*	-
2015	150	39.5*b*	41.2*ab*	41.5*ab*	42.0*ab*	41.0*b*
	200	46.5*a*	46.6*a*	43.5*ab*	47.7*a*	46.1*a*
	av. for N	43.0*a*	43.9*a*	42.5*a*	44.9*a*	-
2016	150	58.0*a*	64.4*a*	58.4*a*	57.9*a*	59.7*a*
	200	63.1*a*	66.4*a*	62.4*a*	62.4*a*	63.6*a*
	av. for N	60.5*a*	65.4*a*	60.4*a*	60.2*a*	-
Hardness of grain (-)						
2014	150	81.3*a*	89.0*a*	83.3*a*	74.5*a*	82.0*a*
	200	84.5*a*	88.5*a*	84.9*a*	90.6*a*	87.1*a*
	av. for N	82.9*a*	88.8*a*	84.1*a*	82.6*a*	-
2015	150	82.3*a*	86.9*a*	84.5*a*	84.7*a*	84.6*a*
	200	83.6*a*	88.2*a*	86.2*a*	89.5*a*	86.9*a*
	av. for N	83.0*a*	87.6*a*	85.4*a*	87.1*a*	-
2016	150	60.5*a*	57.7*a*	56.4*a*	57.1*a*	57.9*b*
	200	59.2*a*	59.6*a*	61.5*a*	59.2*a*	59.9*a*
	av. for N	60.0*a*	58.6*a*	58.9*a*	58.1*a*	-
Test of weight (kg hL^{-1})						
2014	150	80.9*b*	81.1*b*	80.7*b*	81.0*b*	81.0*b*
	200	81.3*ab*	81.7*ab*	81.7*ab*	82.2*a*	81.7*a*
	av. for N	81.1*a*	81.4*a*	81.2*a*	81.6*a*	-
2015	150	79.0*a*	79.9*a*	78.1*a*	78.4*a*	78.9*a*
	200	79.2*a*	79.7*a*	79.9*a*	77.8*a*	79.1*a*
	av. for N	79.1*a*	79.8*a*	79.0*a*	78.1*a*	-
2016	150	74.3*a*	73.1*a*	74.2*a*	73.3*a*	73.7*a*
	200	74.4*a*	74.3*a*	74.4*a*	75.3*a*	74.6*a*
	av. for N	74.4*a*	73.7*a*	74.3*a*	74.3*a*	-

a, *b*, *c*, … values with the same letter are not significantly different according to the Tukey's test ($P \leq 0.05$)

in 2016 were characterised by the highest content of protein and gluten as well as the highest Zeleny index, while the grains harvested in 2014 had the lowest content of these components and the lowest Zeleny index value. RÓŻYŁO et al. (2017) found no significant differences in the protein content of grains, gluten content and the value of the sedimentation index between the N fertilisation levels, and their expected effect was distorted by changing weather conditions in the years of the study. Given that wheat grains are used in the milling and baking industry, grains for baking purposes should contain at least 11.5% protein in the dry matter (Varzakas 2016). The grains of var. Sailor wheat obtained in 2015 and 2016 can be used for the production of flour. On average, irrespective of manganese fertilisation, a higher nitrogen dose increased the protein content by 12.8%, gluten content by 15.7% in the first year of the study, and by 5.7% and 7.6% in the second year of the study, respectively. An increase in nitrogen fertilisation in variants with different Mn doses and without its application promoted an increase in protein and gluten, although the effect was only confirmed statistically in the first year of the study (an increase in the content of protein from 8.5% to 16.6%, and for gluten from 11.9% to 23.6%). Fertilisation with mineral fertilisers combined with manganese increases the protein content (Zeidan et al. 2010, Stępień, Wojtkowiak 2016), gluten content, Zeleny sedimentation index and wheat grain hardness (Stępień, Wojtkowiak 2016). On average, the higher nitrogen dose affected the Zeleny index value by 26.8% during the first and by 12.4% during the second year of the experiment. No significant changes in the starch content of wheat grains were demonstrated. The increase in grain hardness was contributed to by the average fertilisation with 200 kg N ha^{-1} only during the growing season of 2015/2016 and the increase in bulk density of grains during the season of 2013/2014.

Modern plant production, characterised by high fertilisation with nitrogen fertilisers, has an impact on the uptake and concentration of other nutrients (Hamnér et al. 2017). The filling of grains with macro- and micronutrients partially results from the direct allocation from the uptake by the roots and remobilisation of the vegetative tissues by the phloem (Garnett, Graham 2005, Etienne et al. 2018). Depending on the years of the study, the ranges of macronutrient content of wheat grains were, for P, K, Mg and Ca, from 3.00 to 4.00 g kg^{-1}; from 4.03 to 5.33 g kg^{-1}; from 1.13 to 1.33 g kg^{-1}; and from 0.70 to 1.70 g kg^{-1}, respectively (Table 6). The ranges of macronutrient content of the grains were lower than those in studies by Ciołek et al. (2012)

Table 6

Content of macronutrients (P, K, Mg, Ca) of grain under different integrated treatments from 2014 to 2016

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				Av. for doses of Mn
		0.0	0.5	1.0	1.5	
P (g kg^{-1})						
2014	150	3.47*a*	3.50*a*	4.00*a*	3.87*a*	3.71*a*
	200	3.60*a*	3.47*a*	3.00*a*	3.63*a*	3.43*a*
	av. for N	3.53*a*	3.48*a*	3.50*a*	3.75*a*	-
2015	150	3.00*a*	3.23*a*	3.43*a*	3.23*a*	3.22*a*
	200	3.43*a*	3.23*a*	3.23*a*	3.43*a*	3.33*a*
	av. for N	3.20*a*	3.23*a*	3.33*a*	3.33*a*	-

cont. Table 6

Year	Dose of N (kg ha^{-1})	Dose of Mn (kg ha^{-1})				Av. for doses of Mn
		0.0	0.5	1.0	1.5	
2016	150	3.13*a*	3.23*a*	3.13*a*	3.23*a*	3.18*a*
	200	3.20*a*	3.20*a*	3.43*a*	3.13*a*	3.24*a*
	av. for N	3.17*a*	3.22*a*	3.28*a*	3.18*a*	-
K (g kg^{-1})						
2014	150	4.43*a*	4.73*a*	4.10*a*	4.37*a*	4.41*a*
	200	4.60*a*	4.13*a*	4.27*a*	4.60*a*	4.40*a*
	av. for N	4.52*a*	4.43*a*	4.18*a*	4.48*a*	-
2015	150	4.43*a*	4.33*a*	4.03*a*	4.30*a*	4.28*a*
	200	4.30*a*	4.33*a*	4.03*a*	4.23*a*	4.23*a*
	av. for N	4.37*a*	4.33*a*	4.03*a*	4.27*a*	-
2016	150	5.33*a*	5.30*a*	5.03*a*	4.80*a*	5.12*a*
	200	4.33*a*	4.33*a*	4.03*a*	4.33*a*	4.26*b*
	av. for N	4.83*a*	4.81*a*	4.53*a*	4.57*a*	-
Mg (g kg^{-1})						
2014	150	1.17*a*	1.27*a*	1.40*a*	1.27*a*	1.28*a*
	200	1.17*a*	1.20*a*	1.50*a*	1.20*a*	1.27*a*
	av. for N	1.17*a*	1.23*a*	1.45*a*	1.23*a*	-
2015	150	1.18*a*	1.30*a*	1.33*a*	1.33*a*	1.29*a*
	200	1.13*a*	1.20*a*	1.30*a*	1.20*a*	1.21*a*
	av. for N	1.16*b*	1.25*ab*	1.32*a*	1.27*ab*	-
2016	150	1.30*a*	1.33*a*	1.30*a*	1.33*a*	1.32*a*
	200	1.30*a*	1.23*a*	1.30*a*	1.33*a*	1.29*a*
	av. for N	1.30*a*	1.28*a*	1.30*a*	1.33*a*	-
Ca (g kg^{-1})						
2014	150	0.94*b*	1.13*ab*	1.11*b*	1.27*ab*	1.11*b*
	200	1.50*ab*	1.70*a*	1.20*ab*	1.10*b*	1.38*a*
	av. for N	1.22*a*	1.42*a*	1.16*a*	1.18*a*	-
2015	150	0.90*bc*	1.37*a*	1.20*ab*	1.30*a*	1.19*a*
	200	1.53*a*	1.40*a*	0.93*bc*	0.70*c*	1.14*a*
	av. for N	1.16*b*	1.45*a*	1.07*b*	1.00*b*	-
2016	150	0.73*b*	0.80*ab*	0.90*ab*	1.10*ab*	0.88*b*
	200	1.13*a*	0.90*ab*	1.10*ab*	1.13*a*	1.07*a*
	av. for N	0.93*ab*	0.85*b*	1.00*ab*	1.12*a*	-

a, *b*, *c*, … values with the same letter are not significantly different according to the Tukey's test ($P \leq 0.05$)

and by Kwiatkowski et al. (2015). An increase in nitrogen fertilisation from 150 to 200 kg ha^{-1} as well as additional Mn spraying at the stem elongation stage (BBCH 30-31) did not differentiate significantly the P, K and Mg content of wheat grains. According to Hamnér et al. (2017), high N fertilisation (240 kg N ha^{-1}) decreases K concentration in wheat grains. Results of own study and a study by Hamnér et al. (2017) suggest that high nitrogen fertilisation of winter wheat is associated with increased demand of other nutrients as well, in terms of both increased quantities and concentrations in the tissues. Manganese in plants can prevent the uptake and movement of other elements such as Ca, Mg and P, presumably due to the similarity in the ionic radius (Millaleo et al. 2013). Under the influence of the higher N dose (200 kg ha^{-1}), irrespective of foliar Mn spraying, the Ca content of grains increased (by 24.3 and 21.6%, respectively); however, it was only confirmed statistically in the first and third year of the study. Given the combined action of nitrogen fertilisation and manganese application, no effect of these experimental factors on the differentiation of the Ca content was demonstrated, except the application, in 2015, of 1.5 kg Mn ha^{-1} and 200 kg N ha^{-1} (which decreased the Ca content of wheat grains by 46%).

On average, during the study (the years 2014-2016), at the objects fertilised with 150 kg N, an increase in Mn doses resulted in an increase in the P, Mg and Ca content and in a decrease in the weight of 1000 grains, starch content, bulk density of grains, grain hardness and K content (Figure 1). The application of 200 kg N and increasing Mn doses increased the starch content and grain hardness and decreased the percentage of the Ca content.

CONCLUSIONS

1. Nitrogen fertilisation (150 and 200 kg ha^{-1}) and foliar Mn spraying (0.5, 1.0 and 1.5 kg ha^{-1}) had no clear effect on grain yields, technological quality indicators, selected biometric features or the yield components, and the expected results were distorted by the changeable weather conditions.

2. On average, regardless of Mn application, the higher nitrogen dose increased the protein and gluten content as well as the Zeleny index value in the first and the second year of the study. Under the influence of the higher N dose, the Ca content of grains increased; however, it was only statistically confirmed in the first and third years of the study.

3. An increase in nitrogen fertilisation in variants with different Mn doses and without its application promoted an increase in the protein and gluten content, although this effect was only statistically confirmed in the first year of the study.

4. An increase in nitrogen fertilisation from 150 to 200 kg ha^{-1} as well as additional Mn spraying did not significantly differentiate the P, K and Mg content of wheat grains.

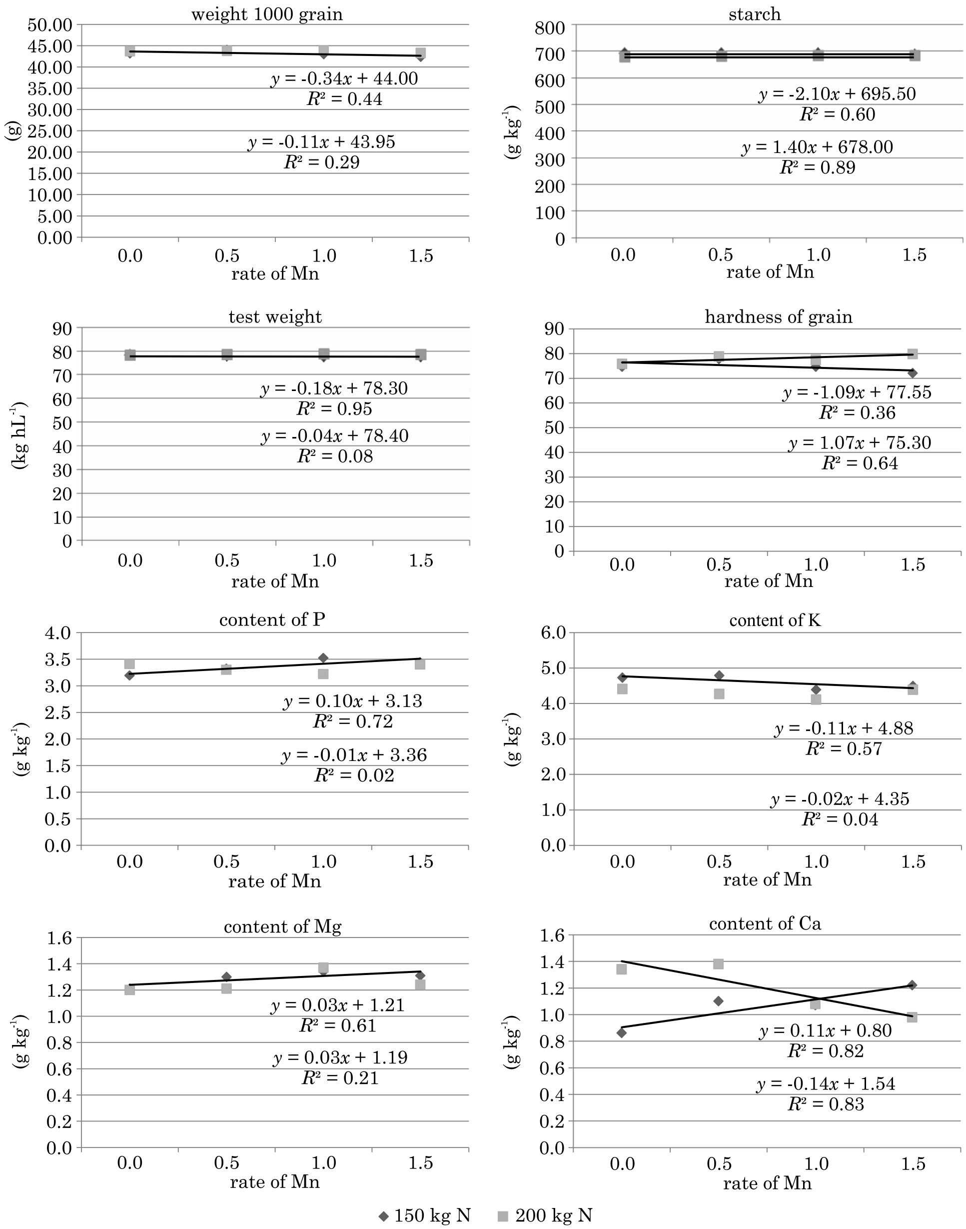

Fig. 1. Trends of the selected variables depends on N fertilisation and Mn foliar application (mean for 2014-2016)

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