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ORIGINAL PAPER

EFFECT OF MINERAL FERTILIZATION ON THE YIELD, BORON CONTENT AND BIOACCUMULATION FACTOR IN GRAIN OF CEREALS*

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Abstract

The following paper presents results on the influence of liming and NPK fertilization on yield and boron content in the grain of spring barley and winter wheat grown on loessial soil. The experiment was set in the Rzeszów Foothills (SE Poland), in a field occupied by controlled fertilizer experiment, according to a randomized block design in four replicates. The average grain yield of spring barley and winter wheat was higher after the liming treatment. For most objects, the NPK fertilization, regardless of liming, significantly increased the grain yields as compared with the trials without fertilization. The highest grain yields were obtained both in non-limed and limed objects after the application of the basic nutrition level ($N_1P_1K_1$). The liming applied, compared to objects without this treatment, considerably increased the boron content in the grain of spring barley (from 1.21 to 1.58 mg kg^{-1} DM) and winter wheat (from 1.49 to 1.73 mg kg^{-1} DM). Limed objects revealed the average values of boron bioaccumulation coefficients for barley and wheat grain (3.1 and 4.1, respectively) higher than achieved in non-limed objects (2.0 and 2.4, respectively). Mineral nutrition, regardless of liming, affected an increase in the boron concentration only in winter wheat grain. The highest boron content (2.25 mg kg^{-1} and 1.89 mg kg^{-1}), as compared to the control, was recorded in the objects where fertilization was applied ($N_1P_1K_0$) and ($N_0P_1K_1$). There was a decrease in the boron content in spring barley grain in the majority of fertilization objects.

Keywords: liming, NPK fertilization, boron, spring barley, winter wheat.

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INTRODUCTION

Among the crop plants for which boron is an essential nutrient, cereals are distinguished by a very low demand for this microelement. Beside reports on toxic boron impact (Cartwright et al. 1986, Benedycka, Kozikowski 1996, Brennan, Adcock 2004, Reid et al. 2004, Yau, Ryan 2008), there are also results indicating negative consequences of the element's deficiency in cereal cultivation (Shorrocks 1997, Wróbel, Sienkiewicz-Cholewa 2003). An appropriate level of boron in food and fodder cereal grain is gaining importance in the context of the research whose results indicate that boron deficiencies in the diet of humans and breeding animals may be the cause of many diseases (Scorei, Popa 2010). Boron deficiency in an organism may lead to an increased incidence of arthritis, osteoporosis and osteoarthritis. Other effects of a low intake of this micronutrient are memory loss, endocrine disorders, decreased libido, and an increased risk of cancer (Scorei, Popa 2010, Popova et al. 2017). Consuming foods containing higher amounts of boron can have chemo-preventive properties (Leszcz, Zaporowska 2013).

Boron is currently the most scarce microelement in soils of humid climate zones. In Poland, a low level of this element is shown in 73% of soils. It was found that up to 91.4% of the spring barley production fields were boron deificient, and 68.4% of the deficiency was revealed in plants (Wróbel, Obojski 1998, Kucharzewski, Dębowski 2000). Deficiencies of this element are found mainly in acid podsolized light sandy soils (Shorrocks 1997).

One of the most important factors affecting the boron availability in soil is pH of the soil solution. In soils with pH < 7, boron is found in the soil solution in the form of undissociated boric acid H_3BO_3, which is readily taken up by a plant root system (Woods 1996). Under such conditions, boron is passively absorbed along with the transpiration stream by plants, although it is also exposed (under conditions of humid climate and light soils) to elution, therefore its availability for plants is very reduced. At pH > 6, boric acid dissociates forming anions $B(OH)_4^-$ in slightly acidic environment and $H_2BO_3^-$ and $B_4O_7^{2-}$ in neutral and alkaline solutions; anions can be easily adsorbed on silty minerals and organic matter particles (Barrow 1989).

Boron is preferably taken up by plants from the soils with pH in the range from pH 5.5 to 6.5. Even on soils with average boron abundance, plants can suffer from its deficiency during cultivation on soils with alkaline or acidic reaction, freshly limed and in periods of drought (Hu, Brown 1997). Boron anions absorbed by plants are partially reduced in the presence of chloride, sulfate and phosphate anions. Increasing the calcium amount reduces the boron uptake, enhances its deficiency, and decreases the toxicity effects. Potassium has similar effects, but it does not limit the boron poisoning results (Hu, Brown 1997). A synergistic interaction of boron and magnesium was reported in the nutrition of barley using fertilizers containing these elements (Benedycka, Kozikowski 1996).

The aim of the study was to determine the influence of liming and mineral fertilization on yield and boron content in the grain of spring barley and winter wheat grown in four rotations on loess soil.

MATERIAL AND METHODS

The research into the effects of liming (A) and mineral fertilization NPK (B) on the yields and boron content in grain of winter wheat and spring barley grown in crop rotation was carried since 1986, on a controlled, long-term fertilizing field of the University of Rzeszow in Krasne near Rzeszow situated in the Rzeszow Foothills (50°02′ N; 22°03′ E, 220 m a.s.l.).

The typical lessive soil (*Haplic luvisol*) on which the experiment was set up was developed from loess and showed the granulometric composition of silt loam. Prior to the experiment, the soil had been characterized by strong acidification of the plough-humus layer (Ap) pH_{KCl} 3.92 and the enrichment layer (Bt) pH_{KCl} 3.89, as well as a very low content of available phosphorus, potassium and a low mean content of available magnesium. The total boron content of 45 mg kg^{-1} in horizon Ap was in the range of natural limits, and forms soluble in 1 mol HCl dm^{-3} represented approximately 1.7% of the total boron content within the soil (Kaniuczak 1996).

The experiment was set up in a random sub-block design in four replicates. The first variable factor was liming (A_2) or its lack (A_1), while the second one consisted of diverse mineral fertilization (B) against the background of constant magnesium nutrition, regardless of liming. The following crops were grown in the crop rotation system: potatoes, spring barley, sunflower fodder and winter wheat. The study covered 4 crop rotation cycles.

NPK fertilization variants included 0.5, 1.0, 1.5 and 2.0 of the basic nitrogen, phosphorus and potassium dose. Basic doses of mineral fertilizers ($N_1P_1K_1$) against the background of constant magnesium nutrition were as follows: spring barley: N_1 = 80 kg N , P_1 = 43.6 kg P, K_1 = 99.6 kg ha^{-1} K, winter wheat: N_1 = 90 kg N, P_1 = 34.9 kg P, K_1 = 83.0 kg ha^{-1} K. Constant magnesium fertilization (24.1 kg ha^{-1} Mg) was applied before sowing in each experimental sub-block. Liming at a dose of 4 t ha^{-1} CaO was used in 1985 prior to the experiment setup and after the harvest of crops completing the rotation. Mineral fertilizers were applied in forms of ammonium nitrate (34% N), triple superphosphate (20.1% P), potassium chloride (48.1% K), magnesium sulfate (9.6% Mg), and calcium oxide (60% CaO) or calcium carbonate (38.9% CaO).

The content of boron in the mineral fertilizers applied in this experiment ranged from trace amounts to: 18 mg kg^{-1} in triple superphosphate, 27 mg kg^{-1} in potassium chloride, 60 mg kg^{-1} in calcium carbonate and 115 mg kg^{-1} in ammonium nitrate. In other fertilizers boron was not detected or trace amounts of boron were found in the lime oxygen (Kaniuczak 1996).

Table 1

Soil reaction before sowing the cereals

Plant	Non-limed soil			Limed soil		
	range of values	average	coefficient of variation (%)	range of values	average	coefficient of variation (%)
Spring barley	3.98-4.21	4.10	1.8	4.62-5.05	5.05	5.0
Winter wheat	4.02-4.51	4.38	2.9	4.80-6.13	5.73	5.7

During the cultivation of winter wheat and spring barley, soil pH in the plough-humus layer (Ap), on specific fertilized objects, especially on non-limed fields, was not very diverse and within a relatively narrow range (Table 1). More significant differences were observed only between non-limed and limed objects (Kaniuczak 1996, Nazarkiewicz, Kaniuczak 2012).

Plant material samples were collected after winter wheat and spring barley harvest. In the dry plant material, boron was determined by means of colorimetry with diantrimid, after dry-ashing (Poulain, Al Mohammad 1995).

The results were statistically processed using a two-factor variance analysis (liming, NPK fertilization) and calculating the Tukey's intervals (LSD) at a significance level of p = 0.05. Linear regression equations and correlation coefficients between selected features were determined. All statistical computations were performed using the software Statistica v.10 and Microsoft Excel 2013. The value of boron bioaccumulation factor in crops (BF) was calculated as a ratio of the element's content in grain to its forms dissolved in 1 mol dm^{-3} HCl contained in the soil (the Rinkis method).

RESULTS

The average grain yield of spring barley (3.77 Mg ha^{-1}) and winter wheat (5.05 Mg ha^{-1}) produced in the four crop rotations on limed field was higher than that achieved on non-limed field (2.31 and 4.56 Mg ha^{-1}, respectively) – Tables 2-3. There was an increase in yields in the limed objects in comparison with the non-limed ones, by 63% for barley and by 11% for wheat. However, these differences between grain yields were statistically insignificant.

Mean yields of barley achieved in non-limed and limed objects were diverse depending on the NPK nutrition level. The non-limed objects produced barley grain yield from 1.69 Mg ha^{-1} to 2.87 Mg ha^{-1}, while limed objects yielded from 3.21 to 4.40 Mg ha^{-1}. The highest barley yields were achieved both from non-limed and limed objects when the basic fertilization

Table 2

Mean values and ranges of spring barley yields (Mg ha^{-1}) depending on liming (A) and mineral fertilization (B)

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
$N_0P_0K_0$	1.69	0.69-2.40	3.21	2.96-3.70	2.45
$N_0P_1K_1$	2.39	1.47-2,91	3.65	3.52-3.90	3.02
$N_{0.5}P_1K_1$	2.38	0,89-3.30	4.03	3.91-4.20	3.21
$N_1P_1K_1$	2.87	1.20-4.40	4.40	4.14-4.70	3.64
$N_{1.5}P_1K_1$	2.34	1.51-3.30	3.51	3.29-3.70	2.92
$N_1P_0K_1$	2.05	1.17-3.00	3.71	2.82-4.30	2.88
$N_1P_{0.5}K_1$	2.34	0.66-3.60	3.99	3.48-4.40	3.17
$N_1P_{1.5}K_1$	2.50	1.11-3.30	4.19	4.09-4.30	3.35
$N_1P_1K_0$	2.12	1.14-3.00	3.78	3.52-4.20	2.95
$N_1P_1K_{0.5}$	2.27	1.26-3.30	3.60	3.10-3.91	2.94
$N_1P_1K_{1.5}$	2.32	1.17-3.40	3.76	3.29-4.10	3.04
$N_{0.5}P_{0.5}K_{0.5}$	2.41	1.14-3.70	3.70	3.24-4.17	3.06
$N_{1.5}P_{1.5}K_{1.5}$	2.51	1.49-3.60	3.85	3.05-4.50	3.18
$N_2P_2K_2$	2.20	1.19-3.20	3.40	2.75-3.90	2.80
Mean (A)	2.31	-	3.77	-	-
LSD at p = 0.05	A = ns, B = 0.62 AB = ns				

A_1 – fertilization NPK + Mg constans, A_2 – fertilization NPK +Mg, Ca constans,
LSD – lowest significant difference for: A – liming, B – mineral fertilization (irrespective of liming), AB – interaction between liming and mineral fertilization,
ns – differences not significant

level was applied ($N_1P_1K_1$). Statistically significant influence of mineral NPK nutrition (B), regardless of liming, on the volume of produced grain yield was recorded only in five objects: $N_{0.5}P_1K_1$, $N_1P_1K_1$, $N_1P_{0.5}K_1$, $N_1P_{1.5}K_1$ and $N_{1.5}P_{1.5}K_{1.5.}$

Winter wheat grown under conditions of constant fertilization yielded at a higher level compared with spring barley. In non-limed objects, the average yields ranged from 3.82 to 5.12 Mg ha^{-1}, while in limed objects they varied from 4.09 to 5.53 Mg ha^{-1}. The effect of mineral NPK fertilization (B) on the yield of winter wheat was more pronounced. For most objects, the NPK nutrition used, regardless of liming, significantly increased the grain yield as compared with the object without such fertilization. The highest average grain yield (5.30 Mg ha^{-1}) was achieved in objects where fertilization was applied ($N_1P_1K_1$). Slightly lower yield of 5.53 Mg ha^{-1} was recorded in limed objects after applying $N_1P_1K_{1.5}$. The lowest wheat yields were obtained in objects where at least one fertilization component was not

Table 3

Mean values and ranges of winter wheat yields (Mg ha^{-1}) depending on liming (A) and mineral fertilization (B)

Treatments of fertilizers	A_1		A_2		Mean(B)
	mean	range	mean	range	
$N_0P_0K_0$	3.82	2.55-5.40	4.09	2.65-5.53	3.95
$N_0P_1K_1$	4.15	2.85-5.40	4.52	2.95-5.63	4.34
$N_{0.5}P_1K_1$	4.55	3.25-6.00	4.97	3.32-6.24	4.76
$N_1P_1K_1$	5.12	3.75-6.60	5.48	3.95-6.86	5.30
$N_{1.5}P_1K_1$	4.87	3.30-6.70	5.14	3.61-6.98	5.00
$N_1P_0K_1$	4.27	3.10-5.80	4.53	3.36-5.94	4.40
$N_1P_{0.5}K_1$	4.54	3.25-5.97	5.03	3.82-6.30	4.78
$N_1P_{1.5}K_1$	5.00	3.60-6.40	5.39	3.98-6.88	5.19
$N_1P_1K_0$	4.53	3.28-6.10	4.99	3.55-6.54	4.76
$N_1P_1K_{0.5}$	4.73	3.30-6.50	5.28	3.69-6.90	5.01
$N_1P_1K_{1.5}$	4.83	3.40-6.60	5.53	3.89-7.20	5.18
$N_{0.5}P_{0.5}K_{0.5}$	4.35	3.35-5.70	5.13	3.69-6.89	4.74
$N_{1.5}P_{1.5}K_{1.5}$	4.79	3.65-6.32	5.38	3.95-6.92	5.09
$N_2P_2K_2$	4.31	3.42-5.80	5.19	3.64-6.50	4.75
Mean (A)	4.56	-	5.05	-	4.80
LSD at p = 0.05	A = ns, B = 0.46 AB = ns				

Explanations as in Table 2

supplied, i.e. ($N_0P_1K_1$) and ($N_1P_0K_1$). Moreover, increasing the N, P, and K doses over the basic fertilization level ($N_1P_1K_1$) caused the lowering of winter wheat grain yield, which was particularly prominent after using the $N_2P_2K_2$ dose.

The interaction of liming with mineral fertilization (AB) in spring barley and winter wheat cultivation has not been confirmed statistically. There was a trend towards higher yield in the limed fertilization objects than in the non-limed ones.

The boron content in barley grain from particular fertilization objects is presented in Table 4. The mean boron quantity in grain of spring barley grown on limed soil (1.58 mg kg^{-1} DM) was remarkably higher than that from non-limed objects (1.21 mg kg^{-1} DM). Moreover, values of the bioaccumulation factor (BF) reflecting the plant's ability to uptake and transport boron from the soil to aerial parts indicates higher mobility of the element in limed objects (Figure 1).

The crops' reaction to liming on individual fertilization objects varied. The boron content higher than average for limed objects was recorded in barley grain only from objects without mineral nutrition $N_0P_0K_0$ and where

Table 4

The content of boron in grain of spring barley (mg kg^{-1} d.m.) cultivated on loessial soil

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
$N_0P_0K_0$	1.05	1.00-1.12	1.87	1.82-2.08	1.46
$N_0P_1K_1$	1.12	1.10-1.14	1.30	1.21-1.39	1.21
$N_{0.5}P_1K_1$	1.22	1.18-1.26	0.83	0.74-1.02	1.03
$N_1P_1K_1$	1.21	1.16-1.26	1.30	1.10-1.40	1.26
$N_{1.5}P_1K_1$	1.19	1.17-1.20	1.20	1.12-1.27	1.20
$N_1P_0K_1$	1.18	1.08-1.30	0.97	0.94-1.22	1.08
$N_1P_{0.5}K_1$	1.22	1.10-1.35	1.03	0.80-1.32	1.13
$N_1P_{1.5}K_1$	1.24	1.15-1.37	1.07	0.90-1.20	1.16
$N_1P_1K_0$	1.28	1.16-1.39	0.97	0.92-1.10	1.12
$N_1P_1K_{0.5}$	1.28	1.18-1.38	1.50	1.44-1.56	1.39
$N_1P_1K_{1.5}$	1.24	1.18-1.30	0.90	0.70-1.10	1.07
$N_{0.5}P_{0.5}K_{0.5}$	1.19	1.09-1.28	2.43	2.04-2.88	1.81
$N_{1.5}P_{1.5}K_{1.5}$	1.29	1.26-1.30	3.27	3.10-3.30	2.28
$N_2P_2K_2$	1.25	1.16-1.35	3.53	3.34-3.58	2.39
Mean (A)	1.21	-	1.58	-	-
LSD at p = 0.05	A = 0.06, B = 0.27 AB = 0.22				

Explanations as in Table 2

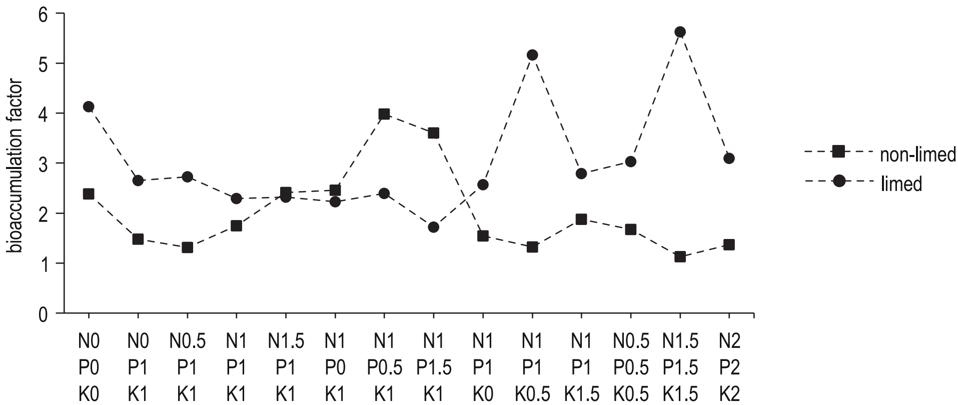

Fig. 1. Bioaccumulation factor (BF) of boron in the grain of spring barley

the following doses of fertilization were applied: $N_{0.5}P_{0.5}K_{0.5}$, $N_{1.5}P_{1.5,}$ $K_{1.5}$, $N_2P_2K_2$ (Table 4).

Mineral nutrition (B), when compared to the control, resulted in a tendency towards decreasing the boron concentration in grain of barley originating from the majority of fertilization objects. Some increase in the boron content in grain owing to fertilization with proportionally increasing NPK doses was also recorded (objects: $N_{0.5}P_{0.5}K_{0.5,}$ $N_{1.5}P_{1.5}K_{1.5,}$ $N_2P_2K_2$).

There was an interaction (LSD for AB significant) of the applied liming and mineral nutrition in shaping the boron content in spring barley grain (Table 4). Liming reduced the boron accumulation in barley grain in several objects, in comparison with non-limed objects. Liming limited boron accumulation to the highest degree in the object where mineral fertilization was at the level $N_{0.5}P_1K_1$ (from 1.22 mg kg^{-1} DM to 0.83 mg kg^{-1} DM) and in $N_1P_1K_{1,5}$ object (from 1.24 mg kg^{-1} DM to 0.90 mg kg^{-1} DM). A distinct decrease in the boron concentration (from 0.21 to 0.31 mg kg^{-1} DM) was also recorded in objects with the fertilization doses $N_1P_0K_1$ and $N_1P_1K_0$.

There was a tendency towards a higher boron content in barley grain owing to mineral nutrition in non-limed objects, particularly after the use of higher N and P doses (Table 4).

Liming significantly enhanced boron concentration in winter wheat grain (Table 5). Average boron content 1.73 mg kg^{-1} from limed objects was remarkably higher than mean value for non-limed objects (1.49 mg kg^{-1}). In majority of limed objects, higher values of boron bioaccumulation factors were recorded as well (Figure 2). Application of diverse NPK doses on lime objects

Table 5

Content of boron in grain of winter wheat (mg kg^{-1} d.m.) cultivated on loessial soil

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
$N_0P_0K_0$	0.84	0.84-0.90	1.13	0.82-1.40	0.99
$N_0P_1K_1$	1.74	1.72-1.80	2.03	1.75-2.28	1.89
$N_{0.5}P_1K_1$	1.32	1.28-1.34	1.67	1.30-2.02	1.49
$N_1P_1K_1$	1.64	1.60-1.72	1.93	1.62-2.20	1.79
$N_{1.5}P_1K_1$	1.57	1.40-1.70	1.80	1.40-2.10	1.68
$N_1P_0K_1$	2.10	2.06-2.26	2.37	2.06-2.68	1.23
$N_1P_{0.5}K_1$	1.70	1.65-1.78	1.93	1.60-2.20	1.82
$N_1P_{1.5}K_1$	1.17	1.04-1.26	1.40	1.10-1.70	1.28
$N_1P_1K_0$	2.17	2.02-2.28	2.33	2.04-2.62	2.25
$N_1P_1K_{0.5}$	1.30	1.08-1.42	1.40	1.06-1.68	1.35
$N_1P_1K_{1.5}$	1.60	1.56-1.76	1.83	1.50-2.10	1.72
$N_{0.5}P_{0.5}K_{0.5}$	1.23	1.02-1.40	1.43	1.02-1.80	1.33
$N_{1.5}P_{1.5}K_{1.5}$	1.20	1.06-1.38	1.57	1.24-1.86	1.38
$N_2P_2K_2$	1.33	1.20-1.50	1.43	1.02-1.90	1.38
Mean (A)	1.49	-	1.73	-	-
LSD at p = 0.05	A = 0.07, B = 0.31 AB = n.s.				

Explanations as in Table 2

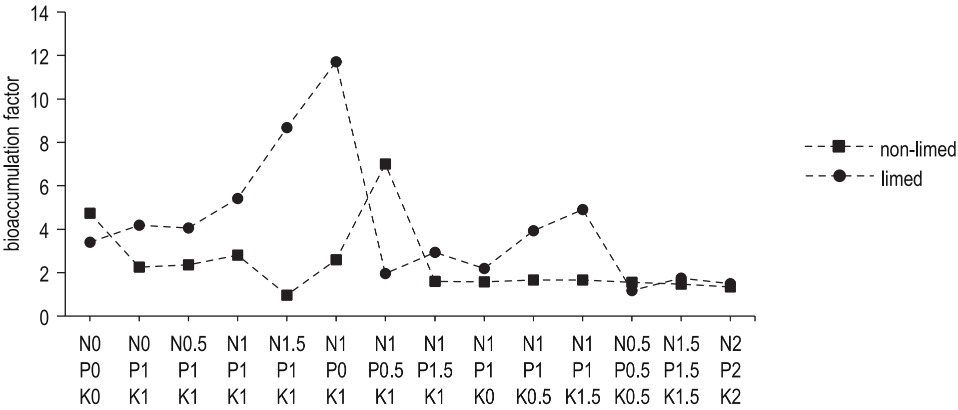

Fig. 2. Bioaccumulation factor (BF) of boron in the grain of winter wheat

caused a significantly greater variety of boron bioaccumulation value rates in grain compared to non-lime objects. In spite of significant diversity, there was no clear influence of NPK fertilization on shaping the bioaccumulation factors (BF) in the grain of the examined cereals.

All objects where liming was applied have shown the trend to increase the boron content in wheat grain (Table 5). The largest increase in this content (from 1.20 mg kg^{-1} DM to 1.57 mg kg^{-1} DM) occurred in the object where mineral nutrition at the level of $N_{1.5}P_{1.5}K_{1.5}$ and $N_{0,5}P_1$ K_1 was applied (from 1.32 mg kg^{-1} DM to1.67 mg kg^{-1} DM).

Mineral fertilization (B), regardless of liming, substantially affected an increase in the boron accumulation in grain in almost all objects, compared with the control. The largest increase in the boron concentration (up to 2.25 mg kg^{-1} and 1.89 mg kg^{-1}) in relation to the control was recorded in the objects where NP ($N_1P_1K_0$) and PK ($N_0P_1K_1$) nutrition was used. These objects were not balanced in terms of N, P, and K doses, i.e. phosphorus fertilization prevailed over nitrogen and potassium doses. Under such conditions, larger amounts of boron were taken up by winter wheat.

The interaction of liming and mineral fertilization (AB) had a positive impact on the trend of increased boron content in grain of winter wheat originating from limed fertilization objects.

DISCUSSION

Changes introduced into the technology of cereal fertilization aim at high yields of grain with good quality characteristics. One of the conditions for obtaining optimum crop yields, in terms of quantity and quality, is to create appropriate soil conditions (Brodowska 2003, Noworolnik 2008*a*, Mühlbachová et al. 2018). In Poland, strong acidification of soils and deficiency of basic nutrients are serious problems in plant nutrition (*Environment* 2015). These factors may reduce crop yields and impair their quality. The present study focused on an analysis of the influence of liming and different NPK doses on the yield of spring barley and winter wheat as well as boron content in grain of these cereals.

Increase in the yield of cereals under the influence of liming and mineral fertilization is quite widely described and discussed in the literature (Mahler, McDole 1987, Brown et al. 2008, Podolska 2008, Kotwica et al. 2011).

Among cereals, winter wheat and spring barley, due to an underdeveloped root system, are plants highly responsive to soil quality. In Poland, the highest yields of spring barley are obtained on soils classified as silt and light loam (5.42 Mg ha^{-1}), and yields even lower by 24% are harvested from slightly loamy sand (Noworolnik 2008a). Wheat yields are the best (6.22 Mg ha^{-1}) on soils classified as light loam, and slightly lower yields (5.95 Mg ha^{-1}) can be achieved on silt. Yielding of spring barley and winter wheat also shows a remarkable dependence on soil pH. High yields of barley are obtained on soils with pH from 5.6 to 6.2, low yields (77% less than the highest yield) are gathered under conditions of pH 4.2-4.8. The highest winter wheat yields are produced at soil pH 6.6-7.2. A gradual decrease in soil pH to 5.9-6.5, and subsequently to 5.0-5.8 and to 4.3-4.9, leads to a substantial decrease in wheat yields (by 10, 19, and 27%, respectively). Winter wheat, as compared to spring barley, is less tolerant to cultivation on acidic soils (Noworolnik 2008*a*,*b*). Mahler and McDole (1987) reported that an increase of pH by 0.2 unit enhanced the winter wheat efficiency from 9% up to 34%. Our study revealed a positive dependence between soil pH and wheat yielding only in limed objects ($y = - 0.9457 + 0.8847$ pH; $r = 0.393$, $p < 0.05$).

The greatest efficiency of both cereals producing grain, regardless of liming, was obtained after an application of the basic fertilization level ($N_1P_1K_1$). With increasing doses of NPK fertilizer above the basic level, there was a significant decrease in yields. Nitrogen fertilization is one of the most important factors affecting both the yield and technological value parameters of cereals. The optimal nitrogen dose for wheat yield reported in the literature depends on a variety and lies within a range from 120 kg N ha^{-1} (Podolska 2008) to 140-165 kg N ha^{-1} (Budzyński et. al. 2004). Higher does do not significantly affect the yield of wheat. Under the conditions of our experiment, nitrogen fertilization exerted greater impact on crop yields in the dose range of N_0-N_1 than phosphorus and potassium nutrition. Both high ($K_{1.5}$ and K_2) and low potassium doses in relation to the basic level of potassium fertilization did not cause a statistically significant increase of the cereal yield (low correlation coefficients, non-significant). Our research, performed under conditions of constant fertilization of a field, revealed a higher boron content in the grain of winter wheat and spring barley being determined in limed objects. The available literature dealing with this subject indicates liming as a cause of reducing (potentially available to plants) the content of soluble boron in the soil, thus limiting its phytoavailability. Lowering the content of available boron along with the soil pH increasing after liming have been also observed by Kumor et. al. (1993), Mercik and Stępień (1994). In earlier studies, Kaniuczak et. al. (2000) reported that liming clearly decreased the element content in the plough-humus layer of the soil (Ap), while stimulating the enrichment of layer Bt (26-50 cm). Dey et al. (2015) as well as Sarkar et al. (2015) found that lime use caused an increase in the plant available boron content in soil.

Frequently conflicting results from studies into the response of boron to soil liming may be attributed to the origin of soil samples from different depths of a soil profile. Routine sampling from the upper (0-20 cm) soil layer to evaluate the abundance of boron meant that the problem of soils with a high content of boron escaped the attention of researchers for many years. Higher boron concentrations associated with higher soil moisture are often encountered in the soil surface (Cartwright et al. 1986). However, boron does not accumulate for a longer time in deeper soil layers. At later stages of development, when a plant develops longer roots, boron nutrition does not improved the way potassium or magnesium availability improves.

Kaniuczak et al. (2000) observed great fluctuations in the boron content in lessive soil during the study years, in addition to which they reported a tendency towards an increase in the soluble boron content in soil resulting from fertilization composed of proportionally increasing NPK doses ($N_0P_0K_0$, $N_{0.5}P_{0.5}K_{0.5}$, $N_1P_1K_1$, $N_{1.5}P_{1.5}K_{1.5}$). Varied mineral NPK nutrition against the background of constant fertilization with other components did not have any significant influence on the content of soluble boron forms in lessive soil developed from loess. Wróbel and Stanisławska-Glubiak (1995), when applying increased NPK doses, observed a deepening decline in the boron content in sandy soil.

Our observations of the objects where high doses of nitrogen were used revealed a high boron content in barley grain, which could arise from the enrichment of the soil with boron along with the doses of ammonium nitrate regularly applied during the study. Boron interactions with N frequently occur due to a change in soil pH as a result of NH_4^+ and NH_3^- uptake. When more NO_3^- is applied or present in the soil, its uptake is increased as compared to NH_4^+, and the rhizosphere pH increases. When more NH_4^+ is absorbed, soil pH decreases (Fageria 2001). Earlier research by Przeszlakowska (1981) had shown that higher nitrogen doses (80 kg N ha^{-1}) could contribute to a decrease in the content of general pectin substances in cereal crops (in straw nodes), and thus a general decrease in the boron concentration ensued. One type of pectin is a branched polysaccharide called rhamnogalacturonan II (RG II). Rhamnogalacturonan II is present in cell walls as a dimer that is bound through covalent bonds with boric acid diesters between apiose moieties in side chains of two RG II monomers (Hu, Brown 1997, Blevins 2009).

Boron concentration in cereals is subject to differentiation depending on a species and cultivar (Korzeniowska 2008). Weather conditions in subsequent years of experiments, affecting the soil humidity and increasing the transpiration rate, can also have impact on extensive variation in the boron content in grain (Hu, Brown 1997).

Wróbel (2009) observed a negative influence of water deficiency on yields and the boron concentration in cereal grains. Under such conditions, only foliage fertilization including boron could alleviated consequences of limited boron availability and considerably enhance the grain yield as well as its content of boron.

The research performed by Korzeniowska (2008) on lessive soil (*Haplic Luvisols*) with acidic reaction and low boron content at fertilization with N – 130 kg ha^{-1}, P – 35 kg ha^{-1}, K – 100 kg ha^{-1} revealed that the boron content in grain of different winter wheat cultivars varied from 2.0 to 2.6 mg kg^{-1}, being 2.3 mg kg^{-1} on average. Even foliar application of 175 g boron per 1 ha did not remarkably increase the element's concentration in grain (2.2-2.6 mg kg^{-1}, an average 2.5 mg kg^{-1}).

Increased boron uptake by barley plants under the influence of phosphorus fertilization was recorded by Mülbachowa et al. (2017) in a pot experiment. High boron concentrations in grain of barley (9.1-14.2 mg kg^{-1}) and wheat (3.8-8.2 mg kg^{-1}) were determined by Cartwright (1986) in soils of southern Australia, which are boron rich, alkaline and saline. Cultivars that accumulate high boron quantities in grain show severe toxicity symptoms – they are weak and produce low yields. The emerging problem of boron toxicity in cereal crops under dry climates has stimulated a considerable progress in research into the molecular and physiological mechanisms of tolerance of barley and wheat to boron toxicity (Schnurbusch et al. 2010).

CONCLUSIONS

1. The average grain yields of spring barley and winter wheat were higher after applying the liming treatment. The NPK fertilization, regardless of liming, increased the grain yields in most objects as compared with the object without fertilization. The highest grain yields were obtained both in non-limed and limed objects after the application of the basic fertilization level ($N_1P_1K_1$).

2. Liming significantly increased the boron content in the grain of winter wheat and spring barley. Mineral nutrition, regardless of liming, increased

the boron content in winter wheat grain. In contrast, the vast majority of the fertilization objects manifested a decrease in the boron concentration in spring barley grain.

3. The interaction of liming with mineral fertilization had no significant effect on the boron content in winter wheat grain. However, there was a trend towards a higher boron content in grain of the winter wheat originating from limed fertilization objects. The interaction of these agrochemical treatments did not clearly affect the boron content in spring barley grain.

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