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ORIGINAL PAPER

INFLUENCE OF LIMING AND MINERAL FERTILIZATION ON THE YIELD AND BORON CONTENT OF POTATO TUBERS (*SOLANUM TUBEROSUM* L.) AND GREEN MASS OF FODDER SUNFLOWER (*HELIANTHUS ANNUUS* L.) CULTIVATED IN LOESS SOIL

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Abstract

The paper presents results of studies on the influence of liming and mineral fertilization on the yields and boron content of potato tubers and green matter of fodder sunflower grown in four and three rotations, respectively, on soil developed from loess. The experiment was set up on a field submitted to long-term fertilization and located in the village Krasne near Rzeszow, lying in the Rzeszów Foothills (Poland). Boron was determined colorimetrically with diantrimide after digestion of dried plant material at 550°C and dissolution of the residue in hydrochloric acid solution. Average yields of potato tubers and green matter of fodder sunflower were higher after liming, but statistical significance was confirmed only for fodder sunflower. Mineral NPK fertilization, regardless of liming, significantly enhanced the yield of green matter of fodder sunflower and, in most fertilization treatments, raised potato tuber yields. Potato tubers accumulated much smaller amounts of boron (2.2-7.5 mg kg^{-1} DM) than aerial parts of fodder sunflower (20-60 mg kg^{-1} DM). The boron content was significantly lower in potato tubers from the limed variant than in plants from the non-limed field. The response of sunflower to soil liming was opposite. The mineral fertilization applied, regardless of liming, had no significant effect on the boron content of potato tubers. Mineral nutrition reduced the boron content in the sunflower biomass under the influence of increasing doses of nitrogen and against the background of constant phosphorus-potassium fertilization.

Keywords: crop yield, boron, liming, mineral fertilization NPK, potato, fodder sunflower.

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INTRODUCTION

Both potatoes and sunflowers belong to popular crops, grown in different regions of the world, including Poland (Kowrygo, Krasnodębska 2009, Gugała et al. 2012). Poland is the 7th largest potato producer in the world, with the total annual yield of potato tubers estimated at 365.4 million tons (GUS 2015). Sunflower is a plant of the warm climate, although it is relatively resistant to drought (Scheiner, Lavado 1999). It is one of the main oil crops that accumulates considerable amounts of boron, meanwhile being particularly sensitive to low concentrations of this element in soil (Asad et al. 2002, Škarpa 2013). According to Szulc and Rutkowska (2013), boron levels present in the soil solutions in Poland are sufficient for cereals and potato, but they do not meet the needs of oil crops and sugar beet.

The chemical composition of agricultural commodities, including the content of macronutrients and microelements, exerts a remarkable influence on the quality of produced food and feeds (Mesquita et al. 2007, Imtiaz et al. 2010). Optimization of agricultural production involves organic and mineral fertilization, which modify the content of elements, including microelements, in cultivated crops (Maier et al. 2002*a*, Wilczek, Ćwintal 2004). This effect relates primarily to the elements constituting the main components used in fertilizers, but very often it is also disclosed in respect of other elements, including those that are not used for fertilization. The reasons include changes in amounts of available forms of elements often caused by an altered soil reaction, sorption and desorption phenomena from the surface of soil particles, the competitive effect of accompanying ions, or changes in the soil redox potential (Kaniuczak et al. 2000, Mercik, Stępień 2000, Tyler, Olsson 2001, Kabata-Pendias 2004, Rutkowska et al. 2009).

Boron is one of the more important micronutrients for plants (Asad 2002, Matoh, Ochiai 2005, Zahoor et al. 2011, Giansoldati et al. 2012), which affects some physiological processes in animal and human organisms (Naghii, Samman 1993, Imtiaz et al. 2010). The boron content in plants depends on their species, variety, developmental stage and organ (Tyler, Olsson 2001, Rashid, Ryan 2004, Giansoldati et al. 2012, Škarpa 2013). Although boron is a readily bioaccumulted element (Kabata-Pendias 2004), deficient boron quantities in cultivated fields are observed relatively often, particularly under humid climate conditions, leading to reduced crop yields (Gupta et al. 1985, Szulc, Rutkowska 2013). A more limited adsorption of boron on soil solid particles at lowered pH aggravates losses of boron due to its leaching down the soil profile (Rutkowska et al. 2009). On the other hand, a problem of excessive and toxic levels of this element arises in arid and semiarid soils as well as in contaminated soils (Gupta et al. 1985, Lucho-Constantino et al. 2005, Camacho-Cristóbal et al. 2008, Frenkel et al. 2010). The interval between the plant deficient and excessive boron content in soils is relatively narrow (Rashid, Ryan 2004, Frenkiel et al. 2010, Szulc, Rutkowska 2013).

At the same time, more intensive crop production requires the use of high doses of mineral fertilizers, hence the need to determine the effects of fertilization on the boron uptake by plants.

Beside soil's richness in available forms and soil pH, the boron concentration in the soil solution depends on the content of colloidal particles and the amount of organic substance (Szulc, Rutkowska 2013). In acidic soils, boron is usually present as H_3BO_3. Plants absorb the element mainly in the form of BO_3^{3-} and $B_4O_7^{2-}$ ions, which are more numerous in neutral and slightly alkaline soils. A marked increase in the soil pH affects the formation of hydroxyl ions $B(OH)_4^-$, which are strongly absorbed by iron and aluminum oxides and by clay minerals (Szulc, Rutkowska 2013), and this effect may reduce the boron uptake by crops. According to Kalembasa and Kuziemska (2013), plants take up boron most intensively from acidic and weakly acidic soils, and its absorption by plants decreases with increasing pH.

The aim of the present study was to determine the influence of liming and mineral NPK fertilization on the yield and boron content in potato tubers (*Solanum tuberosum* L.) and in green matter of fodder sunflower (*Helianthus annuus* L.) grown in loess soil in four and three rotations, respectively.

MATERIAL AND METHODS

The studies on the influence of liming and mineral fertilization on the yields and boron content of potato tubers and green matter of fodder sunflower cultivated in four and three rotations, respectively, were carried out in 1986-2001. The experiment was located on a static fertilization field in Krasne near Rzeszow, in the Rzeszów Foothills (*Podgórze Rzeszowskie*) (Figure 1). The soil in which the experiment was carried out had developed from loess (*Haplic Luvisol*) and contained 0.87 g kg^{-1} DM total N and 7.6 g kg^{-1} DM organic C (Kaniuczak 1998). Prior to the experiment, the soil (0-25 cm) was highly acidic (pH_{H_2O}=4.93, pH_{KCl}=3.92), low in available phosphorus (21.6 mg kg^{-1} DM), potassium (120 mg kg^{-1} DM) and moderately rich in magnesium (73 mg kg^{-1} DM). Among the micronutrients, the content of available boron (0.73 mg kg^{-1} DM), zinc (4.2 mg kg^{-1} DM) and molybdenum (0.08 mg kg^{-1} DM) was low, while the amounts of available manganese (160 mg kg^{-1} DM) and copper (2.7 mg kg^{-1} DM) were moderate. The content of boron soluble in 1 mol HCl dm^{-3} was 0.75 mg kg^{-1} DM in the Ap horizon (0-25 cm) and 0.71 mg kg^{-1} DM in the topmost layer of Bt (25-50 cm). The experiment was set up in a random sub-block design with four replicates. The first variable factor was liming (A_2) or its absence (A_1), while the second one consisted of differeniated mineral fertilization (B) against the background of constant magnesium nutrition. The following crops were cultivated in rotation: potato, spring barley, fodder sunflower, and winter wheat, but sunflower was replaced by fodder cabbage in the 1986-1989 rota-

Fig. 1. Location of the experimental field

tion series. Potato was grown in 1988, 1992, 1996, and 2000, while fodder sunflower appeared in three rotations: in 1990, 1994 and 1998.

NPK fertilization variants included 0.5, 1.0, 1.5 and 2.0 of the basic nitrogen, phosphorus and potassium dose. The basic doses of mineral fertilizers ($N_1P_1K_1$) against the background of constant magnesium nutrition were as follows: potato: N_1 – 120 kg N, P_1 – 43.6 kg P, K_1 – 132.8 kg K ha^{-1}, spring barley: N_1 – 80 kg N, P_1 – 43.6 kg P, K_1 – 99.6 kg K, fodder sunflower: N_1 – 100 kg N, P_1 – 34.9 kg P, K_1 – 99.6 kg K, winter wheat: N_1 – 90 kg N, P_1 – 34.9 kg P, K_1 – 83.0 kg K ha^{-1}, fodder cabbage; N_1 – 120 kg N, P_1 – 26.2 kg P, K_1 – 83.0 kg K ha^{-1}. Constant magnesium fertilization was applied before sowing in each experimental sub-block in 1986-1993, at the dose of 24.1 kg Mg ha^{-1} for potato, spring barley and winter wheat, and 72.4 kg Mg ha^{-1} for fodder crops. Since 1994, the magnesium dose was reduced to 24.1 kg Mg ha^{-1}, applied to all experimental rotation crops. Liming at 4 t CaO ha^{-1} was used in 1985, 1989, 1993 and 1997 prior to starting each rotation and after the harvest of crops completing a rotation series. Mineral fertilizers were applied as ammonium nitrate (34% N), triple superphosphate (20.1% P), potassium salt KCl (48.1% K), magnesium sulfate (9.6% Mg), and calcium fertilizers with contained 60% CaO or 69.5% $CaCO_3$.

The boron content in the applied mineral fertilizers varied: 0-115 mg kg^{-1} in ammonium nitrate, 0-18 mg kg^{-1} in triple superphosphate, 0-27 mg kg^{-1} in potassium salt, and 60 mg kg^{-1} in calcium carbonate (Kaniuczak 1996).

The yields of fresh matter of potato tubers and green mass of fodder sunflower were determined in each year of the study as the mass harvested from plots of 30 m^2. Plant material samples were collected after harvesting potato and fodder sunflower. Boron was determined in dry plant material colorimetrically with diantrimide (Poulain, Al Mohammad 1995) after digestion of the dried plant material at 550°C and dissolution of the residue in hydrochloric acid solution.

The results were presented as medium and value ranges (from 4 years for potatoes, 3 years for sunflower) and statistically processed using two-factor analysis of variance (liming, mineral NPK fertilization), calculating the lowest significant difference (LSD) with the Tukey's tests at the significance level of $p = 0.05$.

RESULTS AND DISCUSSION

In the long-term controlled field experiment, conducted on a field receiving constant fertilization and cropped with plants grown in four-year crop rotation, higher yields of potato tubers and green biomass of fodder sunflower were obtained from limed plots (average yield, regardless of NPK), where they reached 27.8 and 51.8 Mg ha^{-1} FW, respectively, than from non-limed ones (23.8 and 38.7 Mg ha^{-1} FW, on average) – Tables 1, 2. Liming had no statistically significant impact on potato tuber yields, contrary to the yield of fodder sunflower (Tables 1, 2). The mean potato yield from non-limed and limed fields varied depending on mineral NPK nutrition (Table 1). The yield from the non-limed field ranged from 19.3 to 29.7 Mg ha^{-1} FW, while that from the limed field was 20.6-32.5 Mg ha^{-1} FW. Average potato tuber yields recorded in the study (particularly in the variant with liming) were slightly higher than the average yield in Poland (Szulc, Rutkowska 2013, GUS 2015). Results from studies carried out by other authors (Kołodziejczyk 2013, Camargoa et al. 2015) suggest that much higher yields of this crop are attainable.

The mean yields of green matter of fodder sunflower reported in present study fell within quite a wide range: 25.2-46.1 Mg ha^{-1} FW on the non-limed field and 33.4-59.2 Mg ha^{-1} FW on the limed field (Table 2). Doubtless, such variations in the fodder sunflower yields were associated with the differences in mineral NPK fertilization, but the changeable weather conditions in particular years of the study may have been another contributing factor. Mikołajczak et al. (2009) assessed the fresh weight of fodder sunflower yields achieved under Polish conditions at 30-50 Mg ha^{-1}. Pearson et al. (2010)

reported fodder sunflower yields in Colorado (USA) in the range of 6.665-13.625 Mg ha^{-1} DM, which corresponded to 16.7-73.6 Mg ha^{-1} FW. Good productivity of fodder sunflower biomass was confirmed in Pakistan by Siddiqui et al. (2009), Zahoor et al. (2011), Mexico by Escalante-Estrada and Rodríguez-González (2010), and Hungary by Kádár (2011).

In both crops, statistically significant influence of mineral NPK nutrition (B) on yield volume was observed, regardless of liming. This effect was confirmed in the majority of fertilization treatments with potato and all fertilization variants with fodder sunflower (Tables 1, 2). Positive impact of mineral

Table 1

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

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
$N_0 P_0 K_0$	18.0	16.2-21.6	20.6	17.4-25.0	19.3
$N_0 P_1 K_1$	20.5	18.0-23.8	23.8	18.7-29.3	22.1
$N_{0,5} P_1 K_1$	24.3	19.9-26.8	27.1	20.1-33.5	25.7
$N_1 P_1 K_1$	27.0	21.2-30.5	32.2	21.6-40.9	29.6
$N_{1,5} P_1 K_1$	24.8	19.6-27.6	29.6	19.8-38.1	27.2
$N_1 P_0 K_1$	21.9	17.8-27.1	25.3	18.8-28.9	23.6
$N_1 P_{0,5} K_1$	22.6	18.7-27.4	28.1	19.8-33.8	25.3
$N_1 P_{1,5} K_1$	25.8	19.8-28.9	30.0	20.3-36.0	27.9
$N_1 P_1 K_0$	23.2	19.0-28.1	24.1	19.4-28.8	23.7
$N_1 P_1 K_{0,5}$	23.9	20.3-25.8	28.4	20.8-35.9	26.1
$N_1 P_1 K_{1,5}$	25.6	21.5-29.0	31.1	22.5-39.0	28.3
$N_{0,5} P_{0,5} K_{0,5}$	22.9	17.6-26.7	24.3	19.6-27.1	23.6
$N_{1,5} P_{1,5} K_{1,5}$	26.5	21.8-31.2	32.4	23.3-37.8	29.4
$N_2 P_2 K_2$	26.8	20.2-34.5	32.5	22.4-39.0	29.7
Mean (A)	23.8		27.8		-
LSD $p = 0.05$	LSD_A = ns; LSD_B = 5.1 LSD_{AB} = ns				

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

nutrition, mainly nitrogen, on potato and sunflower yields has been reported by many authors (Ruffo et al. 2003, Rymuza, Bombik 2004, Wierzbicka et al. 2008, Siddiqui et al. 2009). For instance, Ruffo et al. (2003) identified a dose of 231 kg N ha^{-1} as required for achieving maximum fodder sunflower yields. Rymuza and Bombik (2004) obtained the highest yields of potato using 420 kg NPK ha^{-1} (120 kg N, 120 kg P_2O_5 and 180 kg K_2O). The results of our study indicate that doses of 120 kg N, 43.6 kg P and 132.8 kg K ha^{-1} ($N_1P_1K_1$) are optimal for potato cultivation (regardless of liming, the mean yields reached 29.6 Mg ha^{-1}), although similar potato tuber yields were achieved in plots with intensive mineral fertilization: $N_2P_2K_2$ and $N_{1,5}P_{1,5}K_{1,5}$. The lowest potato yields were harvested from plots with no fertilization (mean of 19.3 Mg ha^{-1}),

Table 2

Mean values and ranges of green matter of fodder sunflower yields depending on liming (A) and mineral fertilization (B) ($Mg\ ha^{-1}$)

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
$N_0\ P_0\ K_0$	25.2	13.1-37.3	33.4	24.2-42.3	29.3
$N_0\ P_1\ K_1$	35.6	18.2-52.2	46.2	34.9-61.0	40.9
$N_{0,5}\ P_1\ K_1$	41.2	21.2-60.5	52.9	40.2-70.3	47.1
$N_1\ P_1\ K_1$	43.9	22.2-63.3	55.9	41.3-72.3	49.9
$N_{1,5}\ P_1\ K_1$	46.1	23.3-66.5	59.2	43.3-75.8	52.6
$N_1\ P_0\ K_1$	36.5	18.7-53.3	49.8	35.6-62.3	43.2
$N_1\ P_{0,5}\ K_1$	40.2	20.8-59.3	54.0	39.0-68.3	47.1
$N_1\ P_{1,5}\ K_1$	39.3	20.3-58.0	54.3	38.3-67.0	46.8
$N_1\ P_1\ K_0$	38.6	20.1-57.3	52.4	37.9-66.3	45.5
$N_1\ P_1\ K_{0,5}$	39.6	20.8-59.3	53.9	39.0-67.3	46.8
$N_1\ P_1\ K_{1,5}$	39.4	19.8-58.5	54.5	38.2-68.8	46.9
$N_{0,5}\ P_{0,5}\ K_{0,5}$	36.9	19.4-55.3	49.7	36.7-64.3	43.3
$N_{1,5}\ P_{1,5}\ K_{1,5}$	38.5	20.2-57.5	53.4	38.2-66.8	45.9
$N_2\ P_2\ K_2$	40.7	19.4-60.3	55.1	34.1-70.9	47.9
Mean (A)	38.7		51.8		-
LSD p = 0.05	LSD_A =11.0; LSD_B = 5.8 LSD_{AB} = ns				

Explanations as in Table 1.

being slightly lower than in plots where at least one nutrient was omitted (N_0, P_0 or K_0): 22.1-23.7 $Mg\ ha^{-1}$.

The influence of mineral NPK fertilization (B) on fodder sunflower biomass yield was much more prominent – every dose made yields statistically higher than the ones harevsted from the unfertilized plots, and the highest yields (mean of 52.6 $Mg\ ha^{-1}$) were obtained from the variant $N_{1,5}P_1K_1$ (150 kg N, 34.9 kg P, 99.6 kg K ha^{-1}). However, by increasing doses of phosphorus and potassium, the green matter of fodder sunflower yield was reduced, compared to the basic fertilization dose ($N_1P_1K_1$).

The interaction of liming with mineral fertilization (AB), in either potato or fodder sunflower cultivation, was not statistically confirmed. However, a clear tendency for the tested crops to increase yields in all the limed fertilization objects was observed, unlike in the non-limed treatments (Tables 1, 2).

Liming combined with mineral nutrition, through the optimization of soil pH and neutralization of its acidity, supply of nutrients for plants and, frequently, improvement of their phyto-availability, had a positive effect on the crops' yielding. The agricultural practice modified the chemical composition of crops, including the boron content.

The study revealed that the boron content in dry matter of potato tubers ranged within 2.2-7.5 $mg\ kg^{-1}$ DM (Table 3), and its average content (5.1 $mg\ kg^{-1}$ DM) was about 8-fold lower than in the aerial parts of sunflower

Table 3

Mean values and ranges of boron content in potato tubers depending on liming (A) and mineral fertilization (B) (mg kg^{-1} DM)

Treatments of fertilizers	A_1		A_2		Mean (B)
	mean	range	mean	range	
N_0 P_0 K_0	5.7	3.1-7.3	5.2	2.8-6.7	5.5
N_0 P_1 K_1	6.5	5.4-7.4	5.4	5.1-5.8	5.9
$N_{0,5}$ P_1 K_1	6.5	4.9-7.4	4.9	4.7-5.1	5.7
N_1 P_1 K_1	7.1	6.5-7.5	2.6	2.2-3.0	4.8
$N_{1,5}$ P_1 K_1	6.0	4.8-7.3	4.7	4.3-5.3	5.3
N_1 P_0 K_1	5.6	4.6-6.2	4.6	4.4-5.0	5.1
N_1 $P_{0,5}$ K_1	5.6	4.7-6.2	3.8	2.5-4.5	4.7
N_1 $P_{1,5}$ K_1	5.7	4.8-6.3	4.4	4.2-4.6	5.0
N_1 P_1 K_0	5.5	4.4-6.1	4.1	3.9-4.5	4.8
N_1 P_1 $K_{0,5}$	5.4	4.0-6.3	3.9	3.6-4.5	4.6
N_1 P_1 $K_{1,5}$	5.3	3.7-6.3	3.8	3.4-4.5	4.6
$N_{0,5}$ $P_{0,5}$ $K_{0,5}$	5.8	3.8-7.0	4.0	3.0-4.6	4.9
$N_{1,5}$ $P_{1,5}$ $K_{1,5}$	6.3	5.4-6.9	4.3	4.0-4.6	5.3
N_2 P_2 K_2	6.1	4.8-6.9	4.2	3.8-4.6	5.1
Mean (A)	5.9		4.3		-
LSD p = 0.05	LSD_A = 0.3 LSD_B = ns LSD_{AB} = 1.2				

Explanations as in Table 1.

(41.3 mg kg^{-1} DM) – Table 4. The values of boron bioaccumulation coefficients calculated as a ratio of boron in the plant's dry matter to that dissolved in soil (Szulc, Rutkowska 2013) followed a similar pattern and reached 143.0 for sunflower and 13.4 for potato tubers. According to Gupta et al. (1985), a boron concentration in tissues above 15 mg kg^{-1} DM is sufficient for plants and toxicity symptoms can appear at concentrations above 200 mg kg^{-1}. Some crops can tolerate much larger amounts. Asad et al. (2002) noted that B deficiency symptoms were associated with <10 mg kg^{-1} DM in leaves of dicotyledons, but that in monocotyledons they could be induced by just <1 mg kg^{-1}. High requirements of sunflower for boron (along with the remarkable accumulation of this microelement) are confirmed by numerous authors (Gorlach, Gorlach 1983, Asad et al. 2002, Wysokiński et al. 2008, Zahoor et al. 2011, Škarpa 2013). Zerrari and Moustaoui (2005) reported 32.5 mg kg^{-1} DM as a limiting level of boron in sunflower; below this value deficiency symptoms appear. Asad et al. (2002) suggested a threshold of just 25 mg B kg^{-1} in the youngest leaves of this plant (grown under hydroponic experimental conditions). Rashid and Rafique (2005) point out that the critical boron concentration in the shoots of sunflower is significantly higher in younger plants and decreases with age. In our experiment, it was found that the boron content in sunflower from the fertilization treatments (except $N_{1.5}P_1K_1$) did not implicate a risk of boron deficiencies.

Potato tubers usually accumulate much less boron (Gąsior 1996, Fang et al. 2002, Maier et al. 2002*b*, Szulc, Rutkowska 2013). In part, it results from the species' specificity and from the fact that only underground parts of the plant were examined. Significantly higher boron accumulation in aerial plant organs, as compared to roots, was reported by Giansoldati et al. (2012). Baghour et al. (2002) in a field experiment on potato plants found a boron level to be about 21-28 mg kg^{-1} in the dry matter of tubers, 56-83 mg kg^{-1} in shoots and up to 135-173 mg kg^{-1} in leaves.

One of the significant factors affecting the uptake of elements by plants is the soil reaction (Gorlach, Gorlach 1983, Tyler, Olsson 2001, Wysokiński et al. 2008, Szulc, Rutkowska 2013), which substantially determines the solubility and bioavailability of nutrients for plants. Loess soil, in which the experiment was performed, was characterized by significant acidity, and therefore the de-acidification procedure using calcium fertilizers was applied in one of the variants. The effect of this treatment on boron accumulation by the cultivated plants was statistically significant, but different for both species. Potato tubers accumulated on average more boron after the cultivation in the non-limed soil as compared to the average for the limed soil, respectively: 5.9 and 4.3 mg kg^{-1} (Table 3); the sunflower biomass revealed a reverse trend: 40.6 and 42.0 mg kg^{-1}, respectively (Table 4). Rutkowska et al. (2009), when analyzing results from a multi-year fertilization experiment in lessive soil (Albic Luvisols) developed from loess, found an increase in the boron concentration in the soil solution caused by liming. Gorlach and Gorlach (1983), when studying the influence of different doses of $CaCO_3$ and $MgCO_3$

Table 4

Mean values and ranges of boron content in green matter of fodder sunflower depending on liming (A) and mineral fertilization (B) (mg kg^{-1} DM)

Treatments o f fertilizers	A_1		B_2		Mean (B)
	mean	range	mean	range	
N_0 P_0 K_0	32.8	28.0-37.5	48.7	45.0-53.0	40.7
N_0 P_1 K_1	40.7	36.5-46.5	40.7	37.0-45.0	40.7
$N_{0,5}$ P_1 K_1	36.5	32.0-40.5	46.3	43.0-50.0	41.4
N_1 P_1 K_1	39.5	35.5-43.0	37.7	34.0-41.0	38.6
$N_{1,5}$ P_1 K_1	31.8	28.0-35.5	23.8	20.0-26.5	27.8
N_1 P_0 K_1	40.7	35.5-46.5	45.4	40.0-58.5	44.1
N_1 $P_{0,5}$ K_1	51.2	47.0-55.5	43.2	38.0-48.5	47.2
N_1 $P_{1,5}$ K_1	50.2	46.0-55.5	30.7	28.0-34.0	40.4
N_1 P_1 K_0	34.8	31.0-38.5	46.3	42.0-51.0	40.6
N_1 P_1 $K_{0,5}$	44.8	41.0-48.5	40.3	37.0-43.0	42.6
N_1 P_1 $K_{1,5}$	35.3	31.5-39.5	38.5	35.0-42.5	36.9
$N_{0,5}$ $P_{0,5}$ $K_{0,5}$	42.0	38.0-46.0	38.8	36.0-41.5	40.4
$N_{1,5}$ $P_{1,5}$ $K_{1,5}$	39.2	35.5-43.0	49.0	44.0-54.0	44.1
N_2 P_2 K_2	49.0	44.0-55.0	56.0	52.0-60.0	52.5
Mean (A)	40.6		42.0		-
LSD p = 0.05	LSD_A = 0.6; LSD_B = 2.9 LSD_{AB} = 4.1				

Explanations as in Table 1.

applied to strongly acid brown soil, observed a decrease in the boron content in aerial parts of plants along with an increase of the dose of fertilizers used for soil de-acidification. It should be noted that these authors found a slight increase in the amount of boron in the aerial parts of harvested sunflower in a variant with the lowest dose of calcium fertilizers used according to 0.5 hydrolytic acidity of the soil. A decline in the boron uptake by plants with an increasing pH of soils is also indicated by other authors (Dannel et al. 1997, Maier et al. 2002*b*, Wysokiński et al. 2008). Tyler and Olsson (2001) found a very different response to changes in soil pH (adjusted by the addition of calcium carbonate) depending on the analyzed part of the test plant *Agrostis capillaris*. The aerial parts revealed no significant effect of pH on the boron content, but the content of this micronutrient in the roots decreased with pH increasing in the range from 5.2 to 7.8. This corresponds to our results: the content of boron in the underground parts (tubers) of potato from the treament with liming was smaller than that in potato tubers from the non-limed field (Table 3). Regading sunflower, its aerial parts were submitted to analyses and their response was reverse (Table 4). The increase in the boron content of sunflower aerial parts caused by the increasing doses of lime may be due to different mechanisms of the uptake and transport of boron under good (passive) and insufficient (active against the concentration gradient) supply of sunflower plants, as pointed out by Dannel et al. (1997). Gupta and Sanderson (1993) did not find any interaction between the B and Ca uptake by potato plants. Gupta et al. (1985) emphasize that reducing the boron uptake by crops by soil liming may result from the precipitation of hardly soluble sediments (including aluminum hydroxides), which in turn cause an increase in the adsorption of boron to the detriment of the amounts of its soluble forms. However, they underlined that adverse effects appeared only at relatively low pH (about 7) and elevated pH (to 9). It should also be noted that liming of soil (and changes in its pH) may cause different effects on amounts of available boron in various soil layers. Kaniuczak et al. (2000), based on eight years of research conducted on a field with constant fertilization, found that the ploughed humus layer (0-25 cm) of soil was characterized by a significantly higher average content of soluble boron in non-limed treatments, while the top level of the Bt enrichment layer (26 -50 cm) had significantly more boron in limed soil. This could be the result of partial elution of soluble boron (the amount of which increased after liming) from the surface into deeper layers. It means that the uptake of boron, its content in plant tissues and consequently the plant's response to soil liming are also dependent on the depth of the root system. Scheiner and Lavado (1999) confirmed that sunflower plants could absorb water, and thus the nutrients, from deeper soil layers. This may explain the positive influence of liming on the boron content in sunflower green mass documented by years of research.

Mineral NPK fertilization (B), regardless of liming, had a differentiating effect on the boron content in both potatoes and sunflower, as evidenced by different average values from individual fertilization objects. However, the differences for potato tubers were statistically insignificant. The values show a clear tendency for potato tubers to accumulate the largest amounts of boron when grown in the absence or at low doses of nitrogen ($N_{0,5}P_1K_1$, $N_0P_1K_1$, $N_0P_0K_0$) – Table 3. A tendency for lower boron concentrations in potato tubers was reported in treatments with single nitrogen and phosphorus doses, regardless of a potassium dose, as compared to the non-limed variants (5.5 mg kg^{-1}, on average). At the same time, increasing the nitrogen, phosphorus, and potassium doses at a constant N:P:K ratio resulted in a tendency (only for basic dose of $N_1P_1K_1$) to decrease the quantity of boron in potato tubers ($N_0P_0K_0$, $N_{0,5}P_{0,5}K_{0,5}$, $N_1P_1K_1$) – Table 3. Mineral fertilization (B) influenced significantly, albei not univocally, the boron content in the sunflower aerial biomass (Table 4). This effect manifested itself as both an increase in its content (compared to the control) in plots with single nitrogen and potassium doses at the absence or low phosphorus fertilization ($N_1P_0K_1$, $N_1P_{0,5}K_1$) and in plots with the highest NPK doses ($N_{1,5}P_{1,5}K_{1,5}$, $N_2P_2K_2$). In contrast, a decline in the boron content occurred in the variants with elevated nitrogen and potassium doses combined with the constant nutrition with other components ($N_{1,5}P_1K_1$, $N_1P_1K_{1,5}$). The largest quantities of boron were accumulated by sunflower grown at the double doses of nitrogen, phosphorus and potassium (average of 52.5 mg kg^{-1} DM), whilst the lowest boron amounts were determined in plants from $N_{1,5}P_1K_1$ plots (27.8 mg kg^{-1} DM, on average).

The results of our field experiment showed a decreasing tendency for the quantity of boron in the sunflower green mass in response to the increasing nitrogen doses (at constant P_1K_1 fertilization). The effect was particularly pronounced in plants from the limed plots. The lowest nitrogen dose in the cultivation of sunflower slightly increased the boron content in the crop's aerial biomass, but higher doses led to a statistically significant decrease in the concentration of the element, especially remarkable in $N_{1,5}P_1K_1$ variants (Table 4). Thus, the highest decrease in boron in yields was in the objects where the highest yields were achieved. These results coincide with the findings reported by Kaniuczak (1996) from an eigh-yea-long study on the balance of micronutrients in crop rotation supplied mineral fertilizers. The largest accumulation of boron by plants and the largest boron deficit in soils were found of treatments with fertilization ($N_{1,5}P_1K_1$). Also Gąsior (1996) noted a decrease of the boron content in potato tubers supplied increasing nitrogen fertilization doses. In an experiment on *Brassica juncea* Giansoldati et al. (2012) found that nutrition with nitrogen in the form of urea significantly increased the phyto-extraction of boron from soil by aerial parts of plants. Notable was a strong growth in biomass yields with a simultaneous decrease of the boron quantity in tissues under the influence of a higher nitrogen dose. The form of nitrogen fertilizer can have a significant influence on the boron content in plant tissues, as reported by Domagała-Świątkiewicz and Sady (2010), who performed an experiment on cabbage. They concluded that fertilization with nitrate-ammonium solution led to a considerably better accumulation of boron than observed when ammonium sulfate was applied.

Wójcik (2000) underlined better utilization of boron by plants from poorly abundant soils when $Ca(NO_3)_2$ and NH_4NO_3 were used as fertilizers, which may have been caused by associated with weaker adsorption of boron onto aluminum and iron oxides by nitrates. Rutkowska et al. (2009) reported a decrease in boron in the soil solution as a consequence of ammonium nitrate fertilization, which is an indirect effect related to the acidifying action of this fertilizer towards soil.

While analyzing the impact of NPK fertilization, a different response of both plants was found to the fertilization with different doses of phosphorus at constant nitrogen and potassium nutrition (N_1K_1), namely half the basic phosphorus dose ($N_1P_{0,5}K_1$) caused an average statistically significant increase in the boron content of the aerial parts of sunflower, whereas in potato tubers it only caused a decreasing tendency compared to the treatments without phosphorus nutrition ($N_1P_0K_1$). Higher phosphorus doses resulted in a significant decrease in boron concentrations in sunflower plants. The effect of potassium fertilization was similar to that produced by phosphorus fertilization (at a constant dose of nitrogen and phosphorus) on the boron content in dry matter of potato tubers and in sunflower biomass (Tables 3 and 4). Half of the basic potassium dose ($N_1P_1K_{0,5}$) resulted in just a slight increase in the content of boron in sunflower yield compared to the variants without potassium fertilization ($N_1P_1K_0$), but a higher dose effected a significant decrease in the amounts of this element in sunflower versus the control. This relationship was particularly marked in the non-limed plots. In the limed plots, an increase in the potassium dose caused a tendency to reduce the boron content in sunflower. The response of potato tubers to potassium nutrition was similar in the limed objects. In the non-limed objects, only a downward trend was observed. The difference between the boron content of potato tubers, irrespective of liming, was not statistically significant. Studies performed by Kaniuczak (1996) presenting the preliminary balance of micronutrients in loess soil under plant rotation indicated that an increase in phosphorus or potassium doses slightly lowered the boron deficit reported for all fertilization treatments, which could have resulted from the incorporation of this element into the soil along with superphosphate or potassium salt. However, it did not have an univocal influence on boron amounts dissolved in soil and the mean values from the fertilization objects did not differ significantly (Kaniuczak et al. 2000). Rutkowska et al. (2009) found a slight decrease in the boron concentration in the soil solution due to phosphorus and potassium fertilization (at amounts of 50 kg P and 140 K ha^{-1}) in objects without liming, while the limed variants revealed a much more prominent reverse tendency. Similar findings were achieved by Dey et al. (2014), who analyzed boron extracted from soil using hot $CaCl_2$ solution. However, the study did not confirm any positive effect of P and K fertilization on the uptake of boron by potato and sunflower plants. The reason could be the limited uptake of boric acid anion by other anions ($H_2PO_4^-$, Cl^-) introduced to the soil at substantial quantities along with the mineral fertilizers, because interactions between chemical compounds of different elements are known to influence the phytoavailability of some trace elements (Kabata-Pendias 2004, Kalembasa, Kuziemska 2013).

The interaction of liming with mineral nutrition in shaping the boron amounts in the test plants was significant, although different (Tables 3, 4). Potato tubers from the limed fertilization treatments contained less boron levels than the ones grown in non-limed soil. In the sunflower biomass, interactions between the applied cultivation treatments were usually significant, although not univocal (Table 4). Noteworthy are interactions of liming and phosphorous fertilization, which were similar for both test crops. Increased phosphorus doses in limed objects generally caused a reduction in the boron content in both crops.

CONCLUSIONS

1. Average yields of potato tubers and green matter of fodder sunflower were higher after the application of applying, but statistical significance was confirmed only for the fodder sunflower.

2. Mineral NPK fertilization, regardless of liming, significantly enhanced the yield of green matter of fodder sunflower and, in the majority of fertilization treaments, raised potato tuber yields.

3. Potato tubers accumulated much less boron (2.2-7.5 mg kg^{-1} DM), than aerial parts of sunflower (20-60 mg kg^{-1} DM).

4. Liming reduced the boron content in potato tubers. The response of sunflower to liming was opposite.

5. Mineral NPK fertilization, regardless of liming, had no significant influence on boron content in potato tubers. Mineral nutrition decreased boron content in sunflower biomass.

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