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INFLUENCE OF MINERAL FERTILISATION ON THE YIELD AND MACROELEMENT CONTENT IN SUGAR BEET

Konrad Grzegorzewski[1], *Zdzisław Ciećko*[1,2], *Radosław Szostek*[1]

[1]Chair of Environmental Chemistry, University of Warmia and Mazury in Olsztyn
Plac Łódzki 4, 10-727 Olsztyn, Poland
[2]Faculty of Engineering and Management, Higher School of Ecology and Management in Warsaw
Olszewska 12, 00-792 Warszawa, Poland
e-mail: radoslaw.szostek@uwm.edu.pl

Abstract. The aim of this study was to assess the influence of mineral NPK, Mg and micronutrient fertilisation on the content of macroelements and root yield of a sugar beet cultivar called Khazar. The effects of three fertilisation levels were assessed. Additionally, the highest NPK dose was analysed in treatments with NPK + Mg and micronutrients (B, Cu, Zn, Mn). The increasing level of NPK fertilisation as well as the nutrition with magnesium and micronutrients caused an increase in root yield. The highest yield of roots was achieved by beet plants fertilised with the high NPK dose combined with magnesium, boron, copper and zinc. It was demonstrated that roots fertilised with the 3NPK dose and magnesium tended to accumulate more N-total. At the same time, the applied micronutrients contributed to a decline in the N-total content of dry matter in roots. The analysed fertilisation with NPK and micronutrients did not affect the content of phosphorus, potassium and calcium in either of the two beet organs. In general, beet leaves were characterised by higher concentrations of nutrients than roots.

Keywords: sugar beet, NPK, Mg, yield, content of macroelements

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) is a plant distinguished by very high nutritional demands and relatively high production potential. High yields of sugar beet require both mineral and organic fertilisers. It is common knowledge that sugar beet very efficiently absorbs nutrients from manure whose highest soil phytoavailability achieved upon mineralisation coincides with the maximum uptake by sugar plants during the plant growing season. Manure as a fertiliser substantially covers the plant's demand for microelements, except boron. However, the availability of these components from soil can be limited even when their soil content is optimal, for example due to an inadequate soil reaction, antagonisms between ions, or unfavourable weather conditions (Czuba 1993). In agricultural practice, more and more sugar beet producers grow this crop without supplying manure or slurry to soil. In sugar beet cultivation, it is extremely important to determine an adequate level of mineral fertilisation and to balance all minerals properly according to the crop's nutritional requirements. It is also essential to supply both macro- and micronutrients because the latter, as well as having a beneficial effect on the quantity and quality of root yield, improve the resistance of plants to diseases. Paying attention to fertilisation with micronutrients may prove to be particularly important in manure-less cultivation and on soils with neutral reaction, where the supply of micronutrients is lower (Wróbel and Domaradzki 2006). To achieve optimal production outputs, it is essential to supply basic macronutrients, such as N, P, K, Mg, S, C and – under sugar beet – also Na, in the form of mineral fertilisers. It is also reasonable to apply supplementary doses of micronutrients. The ones which are most frequently mentioned as essential in sugar beet production are boron, zinc, copper and manganese (Hellal *et al.* 2009). An adequately designed fertilisation regime, with both macro- and micronutrients, ensures suitable conditions for synthesis of chlorophyll and improved plant productivity (Abdallah and Mekdad 2015, Abdelaal and Sahar 2015).

The technological quality of sugar beet depends on its chemical composition. The content of dry matter and individual constituents in sugar beet roots and leaves is largely shaped by fertilisation, climatic and soil conditions, cultivation treatments and the genetic traits of cultivars. Mineral and natural fertilisers change the physicochemical properties of soil and, simultaneously, affect the chemical composition of sugar beet plants (Barłóg *et al.* 2013a, Grzebisz *et al.* 2012). Sugar beet grown for sugar production is considered to be an industrial crop, and by-products originating from sugar beet root processing (mainly molasses and pulp) make an important contribution to the production of feeds for farm animals. Doses and forms of fertilisers as well as fertilisation timing affect the chemical composition of beet plants and therefore determine the technological utility of beet roots as well as their feed value (Kurus 2006).

The above problems were addressed in the study, reported herein, which was carried out at the Chair of Environmental Chemistry, University of Warmia and Mazury (UWM) in Olsztyn. The objective was to determine the impact of mineral fertilisation, including increasing NPK doses and nutrition with magnesium and micronutrients, on yields of sugar beet and the chemical composition and technological value of beet roots. Sugar beets were grown in a manure-less system.

MATERIAL AND METHODS

The results of a field experiment on the sugar beet cultivar Khazar, conducted in 2002-2004 on a field owned by the Agrofarm Agricultural Farm in Jurkowice near Malbork, underwent analysis. The experiment was set up according to the random blocks method with four replications, on a soil classified in the good wheat complex, class III b (in the Polish soil valuation classification), with the textural composition of medium clay. The soil's agrichemical properties in each year are presented in Table 1.

Table 1. Agrichemical soil properties

Soil properties		Years of the research		
		2002	2003	2004
Type		Medium clay		
Soil valuation class		IIIb		
pH in H_2O		5.76	7.63	5.98
pH in 1M KCl		4.69	7.09	5.67
Hydrolytic acidity (Hh) in mmol $H^+ 100\ g^{-1}$		4.63	1.03	2.59
Phytoavailable forms mg kg^{-1} of soil	P	213.0	269.0	174.0
	K	203.0	961.0	275.0
	Mg	104.0	163.0	76.0
	B	0.91	2.50	0.94
	Mn	132.0	282.0	149.0
	Cu	5.20	7.50	2.90
	Zn	20.1	15.0	7.0
	$N\text{-}NO_3$	2.99	13.40	4.96
	$N\text{-}NH_4$	8.61	6.58	7.82
$C_{organic}$ in g kg^{-1} of soil		17.1	24.6	12.1
N_{total} in g kg^{-1} of soil		1.58	2.42	1.08

The content of available forms of phosphorus, potassium and magnesium was high, while that of the micronutrients – boron, copper, zinc and manganese – oscillated around moderate levels. The meteorological conditions in the years 2002-2004 and in a multi-year period for comparison are presented in Table 2.

Table 2. Weather conditions during the growth and development of sugar beet, Jurkowice

Year	Months							
	04	05	06	07	08	09	10	$\bar{x}$
				Temperature (°C)				
2002	8.3	17.1	16.4	20.0	21.5	13.6	7.0	14.8
2003	7.0	13.9	16.7	19.0	17.7	14.3	6.0	13.5
2004	8.6	11.3	14.7	16.4	19.0	13.6	9.6	13.3
1981-2010	7.9	13.0	15.6	18.1	17.6	13.4	8.7	13.5
				Rainfall (mm)				
2002	15.9	70.0	105.6	46.7	33.7	43.3	138.1	64.8
2003	59.9	40.7	55.2	117.8	39.0	54.4	130.9	71.1
2004	32.0	83.4	67.2	104.8	109.7	54.8	109.8	80.2
1981-2010	35.0	56.6	77.6	77.3	81.0	70.1	64.7	66.0
Σ	142.8	250.7	305.6	346.6	263.4	222.6	443.5	

Mineral fertilisation applied was the experimental factor in our study. Several variants were submitted to analysis: 1) no fertilisation, 2) 1NPK ($N_{40}P_{32}K_{48}$ kg ha^{-1}), 3) 2NPK, 4) 3NPK, 5) 3NPK+Mg, 6) 3NPK+Mg+B, 7) 3NPK+Mg+B+Cu, 8) 3NPK+Mg+B+Cu+Zn and 9) 3NPK+Mg+B+Cu+Zn+Mn. Magnesium was introduced into soil in the form of magnesium sulphate, dosed at 19.3 kg Mg ha^{-1}, and the micronutrients were supplied in the following salts and doses: boron in the form of borax – 2 kg B ha^{-1}; Cu as copper sulphate in an amount of 12.5 kg Cu ha^{-1}; Zn as zinc sulphate in a quantity corresponding to 1.0 kg Zn ha^{-1}, and Mn as manganese sulphate in a dose of 10.0 kg Mn ha^{-1}.

Sugar beets were grown after winter wheat, and their nourishment consisted exclusively of mineral fertilisation according to the above variants. The row spacing was 45 cm x 17 cm. Theoretically, the plant density was 130 thousand plants per ha^{-1}. In the spring, prior to sowing beet seeds, mineral fertilisers were applied to soil: triple superphosphate 46%, potassium salt 60% and ½ of the nitrogen dose in the form of urea 46%. The remaining amount of nitrogen consisted of ammonium nitrate 34%, applied in a topdressing treatment during the sugar beet growth phase of 6 leaves, according to the experiment design. The surface area of the experimental plots was 28 m^2, of which 21.6 m^2 was harvested. During the harvest of beets, the yield of roots and leaves from each plot was determined, and averaged samples of both organs were taken for chemical analyses. The dry matter of the sampled plant organs underwent determinations of: total nitrogen by the Kjeldahl's method, phosphorus by the vanadium-molybdate method, potassium, sodium and calcium by flame photometry, and magnesium by atomic absorption. In this paper, we discuss results on the yield of roots and leaves and their content of macronutrients. The obtained study results were statistically processed using the Statistica 10.0 program, and by the one-way analysis of variance (ANOVA), while the least significant differences (LSD) were determined at a level of significance $\alpha = 0.05$ using the Duncan test (StatSoft 2010).

RESULTS

The root yields harvested in the experiment were high, with an average quantity of 70.7 t ha^{-1} (Fig. 1). The average beet root yield ranged from 67.0 t ha^{-1} in 2002, through 69.4 t ha^{-1} in 2003, up to 75.6 t ha^{-1} in 2004. The differences in root yields between the plant growing seasons were caused by the weather conditions rather than by the tested macro- and micronutrient fertilisation. The three-year average root yield was evidently dependent on the tested fertilisation. The lowest yield was achieved in the control variant, where it equalled 66.3 t ha^{-1}, while the highest one, 72.2 t ha^{-1}, was achieved in the treatment fertilised with the highest NPK dose together with magnesium, boron, copper and zinc. Under the environmental conditions of the experiment, the medium dose of NPK proved to the best at yield formation. The three-year average root yield in this variant was 70.1 t ha^{-1}, which is 5.7% higher than the control. Fertilisation with magnesium and micronutrients, compared with the high NPK dose, did not differentiate much the root yield.

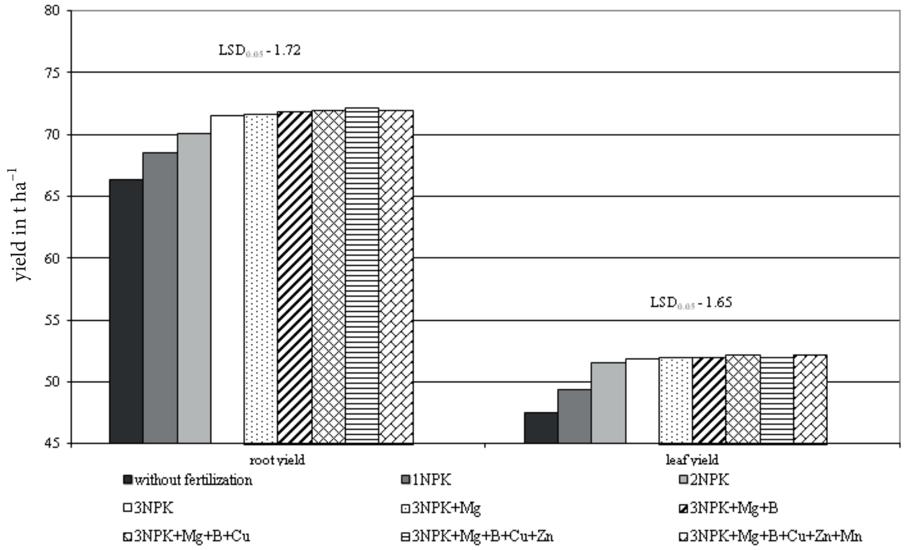

Fig. 1. Influence of NPK, Mg and micronutrient fertilisation on the root and leaf yields of sugar beet in t ha^{-1}, 2002-2004

The average yield of leaves during the whole experiment (2002-2004) was 51.2 t ha^{-1} (fig. 1). The lowest leaf yield mass, 37.4 t ha^{-1} on average, was obtained in 2002. In the same year, the beet plants were also distinguished by the lowest foliage ratio, which was just 0.56. In the consecutive years, the yield of leaves increased significantly. For example, it was 55% higher in 2003 (57.8 t ha^{-1} on average) than in 2002, while the highest leaf yield, 58.3 t ha^{-1}, was harvested in 2004. Significantly higher leaf yields in the second and third year of the experiment were confirmed by the higher foliage ratio values which were 0.83 and 0.77, respectively. As for leaf yield, it should be noted that its quantity clearly corresponded to the NPK fertilisation level. The lowest leaf yield, 47.5 t ha^{-1}, was obtained from the control treatment, that is from an unfertilised variant. A significant increase in leaf yield, by 4% on average, was determined for the plots treated with the low NPK dose. The highest leaf yield, *i.e.* 52.2 t ha^{-1}, was achieved from the plots treated with the highest NPK dose together with magnesium, boron and copper. The medium dose of NPK fertilisers proved to be best at stimulating the leaf yield, analogously to its effect on root yields. The leaf yield produced by plants treated with this dose of NPK was 51.5 t ha^{-1} and exceeded the control by 4 t ha^{-1}, *i.e.* by over 8%.

Total nitrogen determined by the Kjeldahl method. The sugar beet roots in the first year of the experiment contained distinctly more total nitrogen than in the other two years. Its average content in the three consecutive years was 13.0, 8.5 and 5.4 g N kg^{-1}d.m. The mineral fertilisation tested in the study had a stimulating effect on total nitrogen in dry matter of sugar beet rots (Fig. 2). The lowest average nitrogen content in dry matter accumulated in roots from the treatment with the low NPK dose and the one fertilised with the high NPK dose together with the other fertilising components except manganese. The highest N-total content was determined in roots of the beets fertilised with the high NPK dose and the high NPK dose combined with magnesium. The difference between the highest and the lowest N-total was 16% on average.

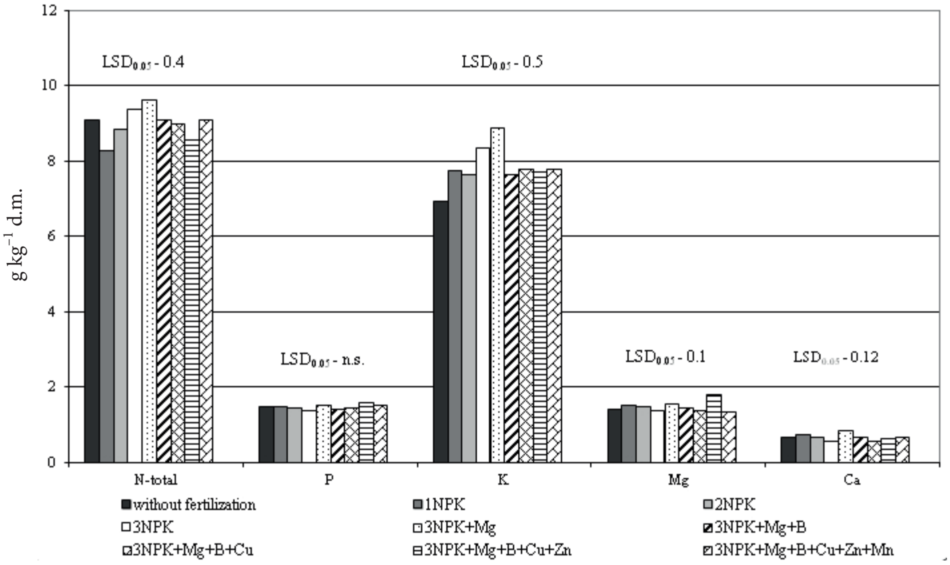

Fig. 2. Influence of NPK, Mg and micronutrient fertilisation on the content of macroelements in sugar beet roots g kg^{-1} d.m., 2002-2004; n.s. – no significant

The tested fertilisation variants modified the nitrogen content in dry matter of leaves. The highest average N-total content, *i.e.* 39.7g N kg^{-1} d.m., was found in the last year of the experiment. In the first two years, leaves accumulated less N-total and its average content was 34.6 in 2002 and 34.4 g N kg^{-1} d.m. in 2003.The applied increasing NPK doses, as well as the fertilisation with magnesium and micronutrients, affected the N-total content of leaves in all the years, that effect being also manifested by the three-year average values (Fig. 3). Of all the tested mineral fertilisation variants, just one combination, namely the high NPK dose with magnesium, boron and copper, caused a significant decrease in the total nitrogen of leaves. In all the other variants, fertilisation caused an increase in the content of N-total of the sugar beet leaves. However, it should be emphasised that the highest average content of N-total in the three years of the experiment, *i.e.* 37.7 g N kg^{-1} d.m., was determined in leaves of sugar beets fertilised with the high NPK dose.

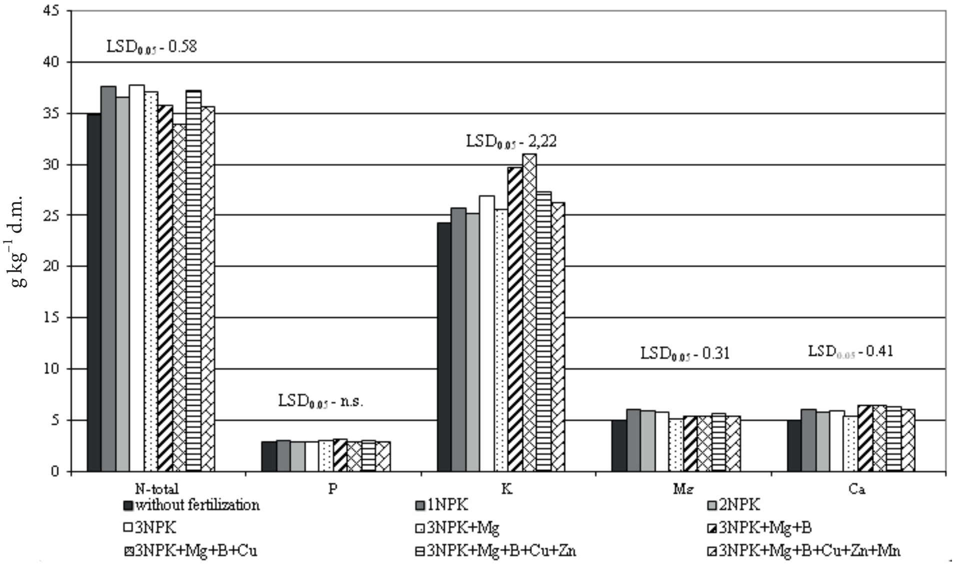

Fig. 3. Influence of NPK, Mg and micronutrient fertilisation on the content of macroelements in sugar beet leaves g kg^{-1} d.m., 2002-2004; n.s. – no significant

Phosphorus. The content of phosphorus in sugar beet roots was year-dependent. A notably higher content of this element was determined in the first year. The average content of phosphorus in beet roots in the consecutive years of the experiment was 1.8, 1.4 and 1.3 g P kg^{-1} d.m. The highest phosphorus content of beet roots relative to the average values in the three years was achieved in the variant fertilised with the high NPK dose together with magnesium, boron, copper and zinc, where its concentration reached 1.6 g in root dry matter (Fig. 2). The lowest average phosphorus content, *i.e.* 1.4 g P kg^{-1} d.m., was detected in the treatment receiving the high NPK dose. The phosphorus content of leaves was also dependent on the years of the study. A distinctly lower content was noted in 2004. The average phosphorus content in sugar beet leaves in the consecutive years was 3.6, 4.0 and 1.3 g P kg^{-1} d.m. The application of mineral fertilisation affected the phosphorus content of the dry matter of leaves. In 2004, and relative to the three-year average, no effect of the increasing NPK doses or the supplementary nourishment with magnesium and micronutrients on the phosphorus content in the dry matter of sugar beet leaves was observed (Fig. 3). In 2002, fertilisation of sugar beets with the medium NPK dose or with the high dose of N_{120} P_{96} K_{144}, including magnesium and the micronutrients: boron, copper and zinc, caused a decrease in the phosphorus content of leaves, down to 3.3 and

3.4 g P kg^{-1} in dry matter of leaves, respectively. In the subsequent year, the lowest content of this element, 3.5 g P kg^{-1} d.m., was determined in the treatment fertilised with all the analysed nutrients. In this variant, phosphorus content was 17% lower than in the control. No effect of fertilisation on phosphorus content in sugar beet leaves was observed in the other fertilisation variants.

Potassium. The content of potassium in sugar beet roots varied between the years of the research. The highest content of this element was noted in the second year, when it reached 9.5 g K kg^{-1} d.m. of roots, on average. It was lower in 2002 (7.6g K kg^{-1} d.m.) and the lowest in 2004 (6.4 g K kg^{-1} d.m.). With respect to the three-year average, the lowest potassium content was determined in roots harvested from the control plots (Fig. 2). The increasing doses of NPK mineral fertilisation and the supplementary application of magnesium caused an increase in potassium content, with the highest concentration, equal to 8.9 g K kg^{-1} d.m. of roots, determined in sugar beets fertilised with the high NPK dose together with magnesium. Regarding beet leaves, the highest average potassium content was found in the second year of the experiment. Its average content in the three consecutive years was 20.5, 35.7 and 24.3 g K kg^{-1} d.m. of leaves. The increasing NPK fertilisation tested in the experiment, and the application of magnesium and micronutrients, caused a significant effect on potassium content, both in the consecutive years of the research and relative to the three-year average (Fig. 3). In variants supplied with the high NPK dose, the supplementary application of boron, copper or zinc, contributed to an increase in the potassium content by 10, 22, 28 and 13%, respectively, compared to the control.

Magnesium. The content of magnesium in beet roots was highly diverse in the years of the experiment (2002-2004). Its highest content was found in the beet roots harvested in 2003, when it reached 1.7 g Mg kg^{-1} d.m. on average. In the other two years it was lower: 1.6 g Mg kg^{-1} d.m. in 2002 and just 1.1 g Mg kg^{-1} d.m. in 2004. The tested fertilisation with increasing NPK doses supplemented with the addition of magnesium and micronutrients against the background of the high NPK level caused changes in the magnesium content of sugar beet roots in all the years of the experiment. The average magnesium content in 2002-2004 depended on the tested mineral fertilisation. The lowest content of this element was determined in the roots of beets supplied with all the analysed nutrients, where it reached 1.3 g Mg kg^{-1} of dry matter on average. An increase in Mg content was observed under the influence of the following fertilisation variants: the highest NPK dose together with magnesium, and with magnesium, boron, copper and zinc. In these treatments, the content of magnesium was 1.6 and 1.8 g Mg kg^{-1} d.m. of roots, respectively (Fig. 2). With regard to beet leaves, the highest magnesium content was determined in leaves harvested in 2004, when it reached 7.2 g Mg kg^{-1} d.m. on average. In the other two years, its average content in leaves was lower and equalled 3.9 g Mg kg^{-1} d.m. in

2002 and 5.5 g Mg kg^{-1} d.m. in 2003. The three-year average content of magnesium was dependent on the tested mineral fertilisation. Its lowest average content equal 5.0 g Mg kg^{-1} was noted in the control (unfertilised) treatment (Fig. 3). No effect of the high NPK dose together with magnesium or with magnesium, boron and copper, or with zinc, on the accumulation of magnesium in beet leaves was documented. The average content of magnesium in these three fertilisation variants was 5.2, 5.3 and 5.3 g Mg kg^{-1} of dry matter. A tendency for increasing Mg concentrations in leaves, versus the control, was observed in the other fertilisation treatments. The highest magnesium content, equal 6.1 g Mg kg^{-1} d.m. of leaves, was achieved by beets fertilised with the low NPK dose.

Calcium. Calcium content of beet roots depended on the year of the experiment. The highest average content of this element, equal 0.9 g Ca kg^{-1} d.m., was determined in the first year. In the other two years, calcium content was significantly lower: 0.5 and 0.6 g Ca kg^{-1} d.m. of roots. The highest calcium content in beet roots relative to the three-year average was determined in the treatment fertilised with the high NPK dose together with magnesium, where it reached 0.9 g Ca kg^{-1} of dry matter of roots. The lowest average calcium content, falling down to 0.5 g Ca kg^{-1} d.m., was detected in the beet roots fertilised with the high NPK dose combined with magnesium, boron and copper nutrition (Fig. 2). The average calcium content of beet leaves in the three consecutive years of the experiment was 3.9, 4.1 and 9.7 g Ca kg^{-1} of dry matter. The accumulation of calcium in sugar beet leaves was affected by the NPK fertilisation applied in the experiment and by the supplementation with magnesium and micronutrients. Our comparison of the three-year average values demonstrates that the highest calcium content in leaves was 6.4 g Ca kg^{-1} d.m., which was determined in the treatment fertilised with the high NPK dose together with magnesium, boron and copper (Fig. 3). Meanwhile, it should be emphasised that the increasing NPK fertilisation together with supplementary doses of magnesium and micronutrients resulted in a tendency for a higher calcium concentration in beet leaves compared to the control treatment.

DISCUSSION

The yields of sugar beet roots were determined more distinctly by the weather conditions in each year than by the tested fertilisation with macro- and micronutrients. The lower yields harvested in 2002 were mostly caused by the deficit of rainfall in July and August, that is the time when the highest root mass increment takes place. In that year, the soil was acidic in reaction and the pH determined in 1 M KCL was 4.69. At such low pH, aluminium compounds, to which sugar beet is highly sensitive, become more toxic (Czuba 1996). This was certainly one of the factors explaining lower yields of sugar beet in the three-year-long experimental period. The negative impact of considerable soil acidity was also demonstrated by Wyszyński *et al.* (2002) in a study which comprised commercial sugar beet plantations. While analysing the data which characterised the soil properties and its richness in nutrients in each year of our research, it can be concluded that the soil in the second year of the experiment had the highest content of macro- and micronutrients, except zinc. Moreover, in the same year, the soil had the most suitable reaction for sugar beet cultivation as well as the highest organic matter content. In short, it was the best soil for growing sugar beet, although the highest yields were obtained in the last year of the trials, which was due to the favourable meteorological conditions throughout the plant growing season. That year was distinguished by favourable rainfall distribution in the critical period as well as beneficial temperatures in September, which together stimulated the highest root yields. The average beet root yield for the three years was clearly dependent on the tested fertilisation. The lowest yield, 66.3 t ha^{-1}, was harvested from the control, while the highest one, 72.2 t ha^{-1}, was achieved from the treatment fertilised with the high NPK dose together with magnesium, boron, copper and zinc. Under the environmental conditions of the experiment, the medium NPK dose, $N_{80}P_{64}K_{96}$, proved to be the best at yield formation. The three-year average root yield in this variant was 70.1 t ha^{-1}, being 3.8 t ha^{-1} higher than the control and 2.0 t ha^{-1} lower than the maximum yield. Similar results were achieved by Michalska-Klimczak and Wyszyński (2010) from a field treated with manure, where the nitrogen dose was raised to 60 and 120 kg N ha^{-1} while the potassium and calcium doses were 80 kg P_2O_5 and 160 kg K_2O ha^{-1}. In their study, the beet root yield at the dose of 60 kg N ha^{-1} was higher by 11.8 t ha^{-1} than in the control, and when the dose was doubled to 120 kg N ha^{-1} the root yield increased by further 3.3 t ha^{-1}. There are references indicating a very strong response of sugar beet to fertilisation with nitrogen as a nutrient, affecting particularly the crop's yields (Barłóg *et al.* 2013b, Grzebisz *et al.* 2012, Abdel-Motagally and Attia 2009). An optimal dose of this nutrient is within the range of 50 to 200 kg N ha^{-1}. Gutmański (1991) suggests a narrower range of doses, between 70-140 kg N ha^{-1}, but emphasises that an optimal dose depends on the soil conditions. Similarly to our experiment, Borówczak *et al.* (2006) found that root yields of sugar beet increased only up to 50 kg N ha^{-1}. The increase in root yield at this level of nitrogen fertilisation, compared to an unfertilised treatment, was 4.3 t ha^{-1}. Further increase of nitrogen doses to 100 and 150 kg N ha^{-1} did not raise the root yields compared to the optimal dose. These results coincide with the ones delivered by Ostrowska and Kucińska (1998) who demonstrated that fertilisation with 120 kg N ha^{-1} caused a slight decrease in root yield relative to the treatment receiving 90 kg N ha^{-1}. Nowakowski (1998) reported a positive effect of higher nitrogen doses on beet root yields up to the fertilisation level of 94 kg N ha^{-1}.

To sum up, the root yields produced by the sugar beet cultivar Khazar under the conditions of our experiment were slightly dependent on the tested mineral fertilisation, while being much more strongly affected by the meteorological conditions. Likewise, Kenter *et al.* (2006) claim that the distribution of precipitations and temperatures as well as their sums during the plant growing season have a very strong impact on the quantity of root yields and root quality in sugar beet.

The yields of leaves, like root yields, were stimulated by the applied increasing NPK doses. The highest leaf yield increase was achieved in 2002, owing to the high dose of NPK applied together with magnesium and micronutrients, where the leaf yield oscillated around 38 t ha^{-1}, although it should be added that the individual micronutrients did not differentiate leaf yield quantity. In the second year, a tendency was observed for higher leaf yields under the influence of the high NPK dose, *i.e.* N_{120} P_{96} K_{144}, together with magnesium, boron and copper, and in the treatment with all the micronutrients, *i.e.* N_{120} P_{96} K_{144} +Mg+B+Cu+Zn+Mn. The average leaf yield in these treatments was 58.4 t ha^{-1}, being 2.0 t ha^{-1} higher than the control. In 2004, a distinct effect of the applied mineral fertilisation on leaf yield was demonstrated, namely higher leaf yields were stimulated by higher NPK doses. The maximum mass of leaves, approximately 60 t ha^{-1}, was obtained in the variants with the highest NPK dose combined with magnesium and the following micronutrients: B, Cu, Zn and Mn. With respect to leaf yields in the individual years as well as the three-year average yield, it can be concluded that the quantity of leaf yields clearly corresponded to the level of NPK fertilisation. The lowest average leaf yield equal 47.5 t ha^{-1} was harvested from the control, unfertilised treatment. A significant increase in leaf yields was noted in the treatment fertilised with the low NPK dose, were it reached 49.4 t ha^{-1}. The highest average leaf yield (52.2 t ha^{-1}) was achieved in the variant fertilised with the high NPK dose combined with magnesium, boron and copper. A positive influence of foliar application of boron on beet root yield was also demonstrated by Dewdar and Abbas (2015) who recorded its significant increase in response to a dose as low as 0.05 g B L^{-1} and the root yields continued to rise as the doses of this micronutrient grew up to 0.25 g B L^{-1}. Similarly to our experiment, a positive impact of copper on beet root yields was demonstrated earlier by Wróbel (1997) who found that a dose of 8 kg Cu ha^{-1} sprayed over leaves led to elevated leaf yields.

Recapitulating our results, it should be noted that the leaf yield in each year was positively affected by the increasing NPK fertilisation. The NPK medium dose of N_{80} P_{64} K_{96} proved to be the best at both leaf and root yield stimulation. The average leaf yield obtained in the plots supplied with this NPK dose was 51.5 t ha^{-1}, thus being higher than the control by 4 t ha^{-1}, *i.e.* by 8%. Similar relationships were reported by Bieniaszewski (1999). In his study, an increase in leaf yield relative to the control, where it equalled 34.4 t ha^{-1}, was 12.6 t ha^{-1} under the influence of N_{60}

P_{48} K_{72} fertilisation, and as much as 21.7 t ha^{-1} in the variant fertilised with N_{120} P_{96} K_{144}. In our experiment, the application of the high NPK dose alongside with magnesium and micronutrients did not raise sugar beet leaf yield, although some tendency appeared for its increase in response to the tested fertilisation. Different results were achieved by Chwil and Szewczuk (2003) who cultivated sugar beets under increasing application of micronutrients (double application of Rolvit B in a dose of 2.5 kg ha^{-1} supplied in the form of sprays) combined with constant soil NPK fertilisation, and demonstrated an increase in root and leaf yield by 18 and 29%, respectively. This dependence can be explained by more efficient action of nutrients when supplied via leaves, which is broadly reported in literature. In the experiment conducted by Wróbel (1996), boron and manganese fertilisation caused a significant increase in average leaf yields. Such large differences in leaf yields and in root yields, described earlier, are caused to a higher extent by the weather conditions than by the applied fertilisation. The increasing NPK doses tested in our research as well as the high NPK dose combined with the application of magnesium and micronutrients had a positive influence on root dry matter nitrogen content. The total nitrogen content in roots also depended on the year of cultivation. In 2002, dry matter of roots contained over twice as much nitrogen as in 2004. Considering the impact of the tested fertilisation on nitrogen content in dry matter of roots, it was not an unambiguous effect, which may have been due to the naturally high soil abundance of nutrients or some elusive soil variability. Similar relationships are noted by Barłóg *et al.* (2002), Buraczyńska *et al.* (2002) and Kurus (2006). As for the three-year average of N-total, noteworthy is a tendency for its higher accumulation in roots fertilised with the high NPK dose and the ones given supplementary magnesium nutrition, as it is well known that magnesium has a beneficial effect on the uptake of nitrogen by plants. Likewise, in the experiment conducted by Kurus (2006), a dose of nitrogen of 120 kg N ha^{-1} caused a significant increase in total nitrogen in sugar beet roots. Another example is found in the study of Buraczyńska (2005), where N_{130} P_{100} K_{170} fertilisation significantly increased the N-total content. In our experiment, roots harvested from the plots fertilised with the lower nitrogen doses contained less total nitrogen, which can be explained by the lower amount of nitrogen brought in with the fertilisers. Also, the fertilisation regime broadened by the application of micronutrients accompanied by the high NPK dose decreased the N-total content, which may have been caused by the catalytic role of micronutrients in the regulation of biochemical processes in plants (Grzyś 2004). The influence of the micronutrients tested in our experiment on nitrogen transformations in plants is also discussed by other authors, mostly with respect to boron (Hellal *et al.* 2009), copper (Kopcewicz and Lewak 2002) and zinc (Barłóg *et al.* 2016). Similar relationships involving N-total have been determined in sugar beet leaves. The doses of NPK, magnesium and micronutrients applied in our study, given the existing environmental conditions, did not produce an unambiguous influence on phosphorus accumulation in roots or in leaves of sugar beet. A tendency, however, was observed for a decrease in phosphorus in both plant organs under the influence of micronutrient fertilisation.

The influence of the tested fertilisation on potassium in root dry matter was not unequivocal, and depended on the year of the research. Against the background of the increasing NPK fertilisation and under the influence of magnesium nourishment, there was a slight increase in the content of potassium in sugar beet roots, up to 8.9 g K kg^{-1} d.m. as a three-year average, but this was not verified in the individual years of the experiment. In the treatments fertilised with the high NPK dose and with magnesium and boron, as well as copper and zinc, the three-year average increase in the potassium content in dry matter of leaves was 10, 22, 28 and 13%, respectively, relative to the control (Fig. 3). Also, in a study performed by Buraczyńska (2005), the $N_{130}P_{100}K_{170}$ dose contributed to an increase in potassium in sugar beet roots and leaves.

The content of magnesium in beet roots depended on the year of cultivation and on the fertilisation with the macronutrient. The least magnesium was determined in yields harvested in 2004. Fertilisation with magnesium favoured the accumulation of this element, while application of magnesium caused a decrease in its content, but these changes were small. In the variants including magnesium, a tendency was observed for its higher accumulation in leaves. The lowest average magnesium content in leaves (5 g Mg kg^{-1} d.m.) was determined in the control, while the results obtained in the treatments fertilised with this element were only slightly higher than the control one (Fig. 3).

The content of calcium in sugar beet roots was also dependent on the year of cultivation, being the highest in the first year (0.9 g Ca kg^{-1} d.m., on average) and the lowest in the second year (0.5 g Ca kg^{-1} d.m.). The NPK mineral fertilisation tested in our experiment, as well as the application of the other elements, did not affect the accumulation of calcium in beet roots. Under the influence of the increasing NPK fertilisation and the broader variant including magnesium and micronutrients, a tendency appeared towards a higher calcium content in leaves. The highest average calcium content, equal 6.4 g Ca kg^{-1} d.m., was determined in leaves harvested from plots fertilised with the high NPK dose together with magnesium, boron and copper (Fig. 3).

Having analysed the effect of the tested elements on the content of macronutrients in sugar beet root dry matter, a conclusion can be drawn that their accumulation was differentiated by the years of cultivation rather than by the various fertilisation treatments. By analogy, Barłóg *et al.* (2002, 2013a) reported that the season-specific factors decided about the variability of the content of mineral components in roots, while the applied fertilisation only slightly affected their uptake by plants. In our experiment, an increasing tendency for the accumulation of macronutrients in response to the increasing NPK doses was observed with respect to nitrogen, potassium and magnesium. In our discussion of the content of macronutrients in sugar beet, it is worth mentioning that high N, P and K concentrations in leaves reduce the spread of sugar beet leaf spot disease caused by *Cercospora beticola Sacc.*, whereas the effect of calcium and magnesium on lowering the pressure on sugar beets by this fungus depends on years of cultivation (Górski 2009). In our research, the plants accumulated the smallest amounts of nutrients in roots in the last year, which was a consequence of the high average yield (75.6 t ha^{-1}) produced in that year. Other authors also attribute this relationship to the so-called 'dilution effect' on nutrients (nitrogen, and Ca, Mg, K and Na cations) which appears as the root biomass grows larger, resulting in lower concentrations of elements (Gawrońska-Kulesza *et al.* 1999, Zimny and Kuc 2005). However, this does not equate to lower unit uptake. Zinc fertilisation stimulated a tendency towards lower accumulation of nutrients in roots, but the relationship was year-dependent. In the current experiment, same as in the studies carried out by Buraczyńska (2005) as well as by Zimny and Kuc (2005), sugar beet roots had a lower content of mineral constituents than leaves did.

CONCLUSIONS

1. Yields of leaves and roots produced by sugar beet as well as their chemical composition were much more strongly dependent on the weather conditions in individual years of the experiment than on the tested fertilisation variants including macro- and micronutrients.

2. The increasing NPK doses as well as fertilisation with magnesium and micronutrients had a positive influence on root yields. The highest root yield, 72.2 t ha^{-1}, was observed in response to the application of boron, copper and zinc. It was higher than the control root yield by 5.9 t ha^{-1}. The medium NPK dose, given the environmental conditions of the experiment, proved to be the most effective in root yield stimulation.

3. In each year, leaf yields were positively affected by the increasing NPK fertilisation. Demonstrably higher yields of leaves were determined under the influence of the low NPK dose. The application of the medium NPK dose proved to be more effective, analogously to the impact on root yields. The high NPK dose in combination with magnesium, boron, copper, zinc and manganese tended to stimulate a further increase in leaf yields.

4. The content of nutrients in sugar beet roots depended mainly on the weather conditions in a given plant growing season and – to a lesser degree – on the applied fertilisation. The micronutrients tested in our experiment contributed to a decrease in total nitrogen in the dry matter of root. The tested fertilisation variants with macro- and micronutrients did not affect significantly the content of phosphorus, potassium

or calcium in either of the examined plant organs. Magnesium application favoured the accumulation of this element in plants, whereas manganese acted antagonistically towards its accumulation. In general, leaves contained more nutrients than roots.

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ODDZIAŁYWANIE NAWOŻENIA MINERALNEGO NA PLONOWANIE I ZAWARTOŚĆ MAKROSKŁADNIKÓW W BURAKU CUKROWYM

Konrad Grzegorzewski[1], *Zdzisław Ciećko*[1,2], *Radosław Szostek*[1]

[1]Katedra Chemii Środowiska, Uniwersytet Warmińsko-Mazurski w Olsztynie
plac Łódzki 4, 10-727 Olsztyn
[2]Wydział Inżynierii i Zarządzania, Wyższa Szkoła Ekologii i Zarządzania w Warszawie
ul. Olszewska 12, 00-792 Warszawa
e-mail: radoslaw.szostek@uwm.edu.pl

Streszczenie. Przedmiotem badań było określenie wpływu nawożenia mineralnego NPK, Mg i mikroelementów na plonowanie buraka cukrowego oraz na zawartość w obu organach tej rośliny tj. w korzeniach i liściach – makroskładników. Do badań wybrano odmianę Khazar. Oceniono efekty trzech poziomów nawożenia NPK. Dodatkowo na tle najwyższej dawki NPK zastosowano magnez oraz mikroelementy – B, Cu, Zn i Mn. Wzrastające nawożenie NPK, jak też nawożenie magnezem i mikroelementami powodowało przyrost plonu korzeni. Najwyższy ich plon otrzymano w obiekcie nawożonym wysoką dawką NPK wraz z magnezem, borem, miedzią i cynkiem. Wykazano tendencję do większej akumulacji N-ogólnego w korzeniach nawożonych dawką 3NPK oraz magnezem. Mikroelementy przyczyniły się do obniżenia zawartości azotu ogólnego w suchej masie korzeni. Rozpatrywane nawożenie NPK i mikroskładnikami nie wpłynęło na zawartość fosforu, potasu i wapnia w obu organach buraka. Ogólnie liście charakteryzowały się większymi zawartościami składników pokarmowych niż korzenie.

Słowa kluczowe: burak cukrowy, NPK, Mg, mikroelementy, plon, zawartość makroskładników