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Effect of zinc band application on sugar beet yield, quality and nutrient uptake

P. Barłóg, A. Nowacka, R. Błaszyk

Department of Agricultural Chemistry and Environmental Biogeochemistry, University of Life Sciences, Poznan, Poland

ABSTRACT

The yield-forming effect of sugar beet fertilization with nitrogen (N) depends on many factors, including the components controlling N metabolism such as zinc (Zn). Two field experiments on soil with an average content of available Zn were conducted to verify the hypothesis. The component was deep band-applied in the form of ZnO suspension together with urea ammonium nitrate, UAN (72 kg/ha). The rates of Zn were as follows: 0; 0.5; 1.0; 1.5 and 2.0 kg/ha. The beet yield (BY) increased in accordance with the Zn rate. The significant BY increase compared to the control was recorded at a level of 1.5 and 2.0 Zn kg/ha, amounting to 14.5% and 21.8%, respectively. The best quality of taproots reflected in biological sugar content was observed at a level of 0.5 kg/ha. In the result, already the rate of 0.5 kg/ha significantly increased sugar yield compared to the control. The effect of Zn application on the nutrient content and uptake depended on the vegetation season, investigated part of the plant and the element. The examined factor significantly affected Zn content in leaves and N in the taproots. Only a total Zn uptake, independently of the seasonal factor, considerably depended on the fertilization applied.

Keywords: *Beta vulgaris*; leaves yield; micronutrient; subsurface banding; zinc oxide

The basic principles of proper fertilization of sugar beet mainly relate to the skilful management of nitrogen (N). This is due to the fact that this component to the greatest extent controls the rate of plant growth, assimilation surface, assimilates distribution between leaves and roots, and thus the yield and quality of the roots (Hergert 2010). Increased effectiveness of N fertilization can be achieved using various methods. The most important ones include: optimization of all non-nutritional growth factors; improvement in soil productivity, e.g. soil pH; use of new formulas of fertilizers and fertilization methods; balanced nitrogen fertilization (Barłóg et al. 2010). The last requirement relates to the balancing of N doses with the compounds controlling this component metabolism. These also include Zn (Hafeez et al. 2013).

The most important biochemical and physiological functions of Zn in plants include: participation in biosynthesis of tryptophan – the precursor of auxins; control of carbonic anhydrase; activation of RNA polymerase; stabilization of cytoplasmic membranes; control of oxidative stress through superoxide dismutase and increased plants resistance to water stress (Khan et al. 2004, Lošák et al. 2011, Hafeez et al. 2013).

Among the micronutrients, the sugar beet exhibits the greatest sensitivity to the deficiency of boron, manganese and copper in the soil. Compared to these elements, sugar beet appears to be a very good forager for Zn and deficiency symptoms are not very common (Christenson and Draycott 2006). Nevertheless, there are some current data in the literature indicating that it may be a factor limiting beet yield, in particular in alkaline soils (Neamatollahi et al. 2013, Goborah et al. 2014). In the countries of the temperate zone, except pH, Zn deficiency in sugar beet may be caused by such factors as: lack of organic manure; high frequency

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of sensitive crops cultivation; too high phosphorus (P) rates (Barker and Eaton 2015). Foliar Zn application is recommended due to strong absorption of Zn^{2+} ions in the soil. However, the literature data are not conclusive and do not always emphasize the purposefulness of this treatment. Moreover, the studies show that the use of micronutrients mixture brings more benefits than just the application of one of them, including Zn (Zeinab et al. 2011, Goborah et al. 2014). An alternative way of Zn incorporation into the soil, next to the broadcast fertilization, can be seed-row application (Stevens and Mesbach 2005).

The aim of the study was to determine the influence of deep-banding of zinc fertilizer (ZnO), together with urea ammonium-nitrate solution, on the yield and quality of sugar beet as well as nutrient content and uptake.

MATERIAL AND METHODS

The study was conducted in 2004–2005 in western Poland, on a farm in Racot (52°03'N, 16°42'E). An effect of Zn application was investigated at five levels: 0; 0.5; 1.0; 1.5 and 2.0 kg Zn/ha. The experiment was conducted in a randomized block design with four replications in plots of an area of 54 m^2. Zinc was applied in a form of ZnO (Zintrac 700). Zinc fertilization was combined with simultaneous deep-band application of urea ammonium nitrate solution (UAN, 28-0-0). The rate of UAN was 72 kg N/ha and fertilizer with the addition of ZnO suspension was placed 6 cm from the row of seeds at a depth of their sowing. Potassium fertilizer (Korn-Kali 40) was used at pre-sowing in autumn, at a rate of 133 kg K/ha.

The long-term average total yearly precipitation in the area of study is about 550 mm. During the study, whole annual precipitation amounted to 458 mm (2004) and 581 mm (2005). It should be noted that in the two critical months for sugar beet growth (July and August) the amount of rainfall was 102 mm (2004) and 146 mm (2005). The requirements for water by the sugar beet canopy in both months are fixed at the level of ca 180 mm. The average annual temperature was 9.3°C in 2004 and 9.1°C in 2005.

According to the World Reference Base for Soil Resources (WRB), the soils have been classified as Luvisols. They are characterised by light loam textures. Soil reaction (pH) in the arable layer was 6.7–6.8 in a suspension of 1 mol/L KCl. In 2004, the soil was characterised by a very high concentration of P (139 mg/kg) and the moderate one of K (106 mg/kg). In 2005, the concentration of both P and K was very high (111 and 196 mg/kg). Plant-available P and K were determined by DL method. Zinc content in the soil was in the middle class and was 12.3 and 8.0 mg/kg in 2004 and 2005 (1 mol/L HCl, Rinkis method).

The fore crop was spring barley. Sowing of the Hetman cultivar seeds was conducted on 8 April 2004 and 4 April 2005. A standard plant protection was applied. Sugar beets were hand-harvested at the stage of technological maturity (49 BBCH) from an area of 14.4 m^2. The evaluation of qualitative parameters of storage roots (BY) was performed by using a Venema auto-analyser IIIG (Groningen, the Netherlands). White sugar yield (WSY) was calculated according to the Brunswick formula (Buchholz et al. 1995):

$$SML = 0.12\ (K_q + Na_q) + 0.24\ AmN + 1.08$$

$$WSC = SC - SML$$

$$WSY = (BY \times WSC)/100$$

Where: SML – standard molasses loss (%); $K_q + Na_q$ – sum of potassium and sodium (mmol/100 g); AmN – α-amino-N (mmol/100 g); SC – sucrose concentration (%); BY – beet yield (t/ha); WSC – white sugar concentration (%); WSY – white sugar yield (t/ha).

Sucrose concentration in fresh taproots was determined by polarimetry, K_q and Na_q by flame photometry, and AmN was analysed by the fluorometric ortho-phthaldialdehyde (OPA) method.

Total N content was determined using the Kjeldahl method. In order to determine the content of other components, plant samples were mineralized (550°C), and then dissolved in HNO_3 solution. Cations were determined by atomic absorption spectrophotometry and P using the colorimetric method with ammonium molybdate-vanadate. The effect of individual research factors (year, fertilization) and the interaction between them was assessed by means of two-way ANOVA. Differences between the mean values were compared by the Tukey's method, where the significance level was α = 0.05. STATISTICA 10 software (StatSoft, Inc., Tulsa, USA) was used for statistical analyses.

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RESULTS AND DISCUSSION

The vegetation season and Zn fertilization were the factors significantly differentiating the beet yield (BY). No significant interaction of both factors was noted. Beet yield increased with increasing Zn doses. Both in the first and in the second year of the study, the highest BY was obtained at a level of 2.0 kg Zn/ha. On average for two years of the study, significant BY increase compared to the control was observed at levels 1.5 and 2.0 kg Zn/ha (Table 1). The optimal rate of Zn applied using the traditional broadcast method in the form of $ZnSO_4$, is about 8–16 kg Zn/ha (Wróbel 2002, Neamatollahi et al. 2013). Depending on the pH of the soil, it allows BY increase by 3–10% compared to the control. According to Goborah et al. (2014), twice foliar spraying with Zn resulted in BY increase by 3.8%. Foliar application of Zn increases the area of sugar beet leaves, as well as the content of chlorophyll and carotenoids in them (Zeinab et al. 2011). According to Stevens and Mesbah (2005), banded application of Zn is better than foliar method. This method allows 11% BY increase using only 2.3 kg Zn/ha. In turn, it can be concluded from the study conducted by Potarzycki et al. (2015) that foliar application of Zn in corn is better than soil application of this component. However, the authors applied Zn in soil using traditional method, i.e., on soil surface. In this study, the maximum BY increases were 13.0% (2004) and 30.9% (2005). Zinc content in the analysed soil samples was in the optimal range. Nevertheless, higher BY increase under Zn influence was obtained on the soil poorer in Zn (2005). The pH of the investigated soils was close to neutral, and thus the activity of Zn^{2+} ions was lower than in the acidic pH. In addition, the soil was characterized by a very high concentration of P, that directly reduces plant available Zn (Hafeez et al. 2013). Moreover, no manure was used in the experiments. This may also explain the high yield-forming efficiency of deep-band applied Zn. According to Stevens and Mesbah (2005) good supply of sugar beet in Zn at the beginning of vegetation provides fast growth of sugar beet. It was exactly the case of our study. This phenomenon can be explained by the increase in indole-3-acetic-acid and endogenic gibberellin concentration in plant roots fertilized with zinc (Barker and Eaton 2015). Faster covering of the rows by the leaves means not only a larger area of assimilation, but also more efficient use of water and N from the soil (Malnou et al. 2006).

Unlike in the BY, only the vegetation season was the factor significantly differentiating the leaf yield (LY). The trend to decrease the LY in the variants with Zn was observed compared to the control. As a result, the average value of foliage coefficient was subject to a decrease with Zn dose (Table 1). The result obtained proves that this element favourably affected the distribution of assimilates and plants maturation process.

Zinc fertilization significantly affected the quality of sugar beet. The trend to increase sugar content (SC) value under the influence of fertilizer application at a rate of 0.5 kg Zn/ha was observed in each year. Zinc rates larger than the optimal one reduced SC, which can be explained by the effect of dilution. In relation to AmN and K_q, the fertilization effect was modified by the seasonal factor (Table 2). According to the literature, foliar

Table 1. Effect of zinc deep-band application on beet yield, leaves yield and foliage coefficient

Zn rate (kg/ha)	Beet yield (t/ha)			Leaves yield (t/ha)			Foliage coefficient		
	2004	2005	mean	2004	2005	mean	2004	2005	mean
0	57.1	55.6	56.4^{a}	23.5	37.4	30.5	0.41	0.67	0.54^{a}
1.5	60.1	61.4	60.7^{ab}	20.7	32.7	26.7	0.34	0.53	0.44^{ab}
1.0	60.5	63.2	61.9^{ab}	20.9	33.6	27.3	0.35	0.53	0.44^{ab}
1.5	63.0	66.3	64.6^{bc}	20.8	34.7	27.8	0.33	0.52	0.43^{ab}
2.0	64.5	72.8	68.7^{c}	24.6	31.7	28.2	0.38	0.44	0.41^{b}
Mean	61.0	63.9	62.5	22.1	34.0	28.1	0.36	0.53	0.45

Homogeneous groups of treatments (for α = 0.05)

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Table 2. Effect of zinc deep-band application on beet quality and white sugar yield

Year	Zn rate (kg/ha)	SC (%)	AmN	K_q	Na_q	SML	WSC	WSY (t/ha)
			(mmol/100 g)			(%)		
2004	0	18.5	2.11	3.94	0.52	2.12	16.3	9.3
	0.5	19.7	1.56	3.68	0.47	1.95	17.8	10.7
	1.0	19.8	1.64	3.69	0.47	1.97	17.9	10.8
	1.5	19.3	1.65	3.75	0.48	1.98	17.4	10.9
	2.0	19.3	1.91	3.67	0.53	2.04	17.3	11.2
2005	0	18.9	1.74[c]	4.98[b]	0.42	2.15	16.8	9.4
	0.5	20.3	1.73[bc]	4.39[ab]	0.39	2.07	18.3	11.2
	1.0	19.6	1.36[ab]	4.05[ab]	0.39	1.94	17.6	11.1
	1.5	19.8	1.33[ab]	3.99[ab]	0.34	1.92	17.9	11.9
	2.0	19.5	1.06[a]	3.75[a]	0.34	1.83	17.6	12.8
Mean	0	18.7[a]	1.93	4.46[b]	0.47	2.13[b]	16.6[a]	9.3[a]
	0.5	20.0[b]	1.65	4.03[ab]	0.43	2.01[ab]	18.0[b]	10.9[b]
	1.0	19.7[ab]	1.50	3.87[a]	0.43	1.96[a]	17.7[ab]	11.0[b]
	1.5	19.6[ab]	1.49	3.87[a]	0.41	1.95[a]	17.6[ab]	11.4[b]
	2.0	19.4[ab]	1.48	3.71[a]	0.43	1.93[a]	17.5[ab]	12.0[b]

Homogeneous groups of treatments (for α = 0.05). SC – concentration of sucrose; AmN – α-amino-N; K_q – potassium; Na_q – sodium; WSC – white sugar concentration; SML – standard molasses loss; WSY – white sugar yield

application with Zn can improve the quality of taproots by SC increase (about 0.99%) and decrease in concentration of K_q, Na_q and AmN (Gobarah et al. 2014). According to the authors cited above, Zn application caused also a decrease in SML value from 3.66–3.55%, and concurrently an increased WSC (15.57% → 16.66%). The authors concluded however, that the combined application of four

Table 3. Effect of zinc deep band application on nutrient content in leaves and taproots of sugar beet (mean for 2004–2005)

Zn rate (kg/ha)	N	P	K	Na	Ca	Mg	Zn	Mn	Cu
	(%)						(mg/kg)		
Leaves									
0	2.71	0.31	4.09	2.32	0.69	0.74	23.0[a]	78.1	7.8
0.5	2.48	0.32	4.04	2.04	0.71	0.72	25.2[ab]	85.9	6.9
1.0	2.55	0.31	3.68	2.07	0.86	0.76	30.8[b]	92.2	7.1
1.5	2.55	0.31	3.65	2.04	0.80	0.70	27.0[ab]	81.8	7.3
2.0	2.51	0.29	3.63	2.04	0.83	0.72	27.3[ab]	82.1	6.9
Year × Zn	ns	ns	ns	s	s	ns	ns	ns	ns
Taproots									
0	0.55[b]	0.05	0.51[b]	0.04	0.11	0.12	15.4	31.0	4.4
0.5	0.44[ab]	0.06	0.50[ab]	0.03	0.10	0.10	16.2	27.8	3.9
1.0	0.39[a]	0.06	0.41[ab]	0.03	0.10	0.11	16.4	29.6	4.0
1.5	0.41[a]	0.04	0.39[a]	0.03	0.11	0.11	19.2	36.3	5.3
2.0	0.49[ab]	0.04	0.38[a]	0.04	0.10	0.11	17.5	19.0	3.7
Year × Zn	ns	ns	ns	s	s	ns	ns	ns	ns

Homogeneous groups of treatments (for α = 0.05). Interaction between year and Zn application: s – significant; ns – non significant

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Table 4. Relationships between Zn (x) content and accumulation and white sugar yield (WSY) depending on the year and plant organ

Feature	Plant part	Year	Equation	R^2 (n = 5)
Zn content	leaves	2004	$WSY = -19.0 + 1.81x - 0.027x^2$	0.85
		2005	$WSY = -45.5 + 5.08x - 0.113x^2$	0.98*
	taproots	2004	$WSY = -5.27 + 0.72x$	0.89*
		2005	$WSY = -11.5 + 1.72x$	0.77*
Zn accumulation	total	2004	$WSY = -25.7 + 0.148x - 0.0001x^2$	0.98***
		2005	$WSY = -0.313 + 0.032x$	0.94

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

microelements (B + Mn + Zn + Fe) provides better beet quality than Zn alone. In our study, the rate optimal due to SML and WSC values was 0.5 kg Zn/ha. The investigated factor increased WSY value in each year. As a result, the average WSY values, compared to the control, increased depending on the rate of the component from 17.8–28.9% (Table 2).

The main factor determining the chemical composition of leaves and taproots was the vegetation season. On average, the highest concentration of Zn in leaves was obtained after an application of 1.0 kg Zn/ha, while in the taproots it was 1.5 kg Zn/ha. Moreover, the trend for further reduction of N and K content with increasing Zn doses was observed in the taproots (Table 3). In 2004, the relationships between Zn concentration in sugar beet organs with WSYs were described the best using 2° regression equations. In turn, linear relationships were obtained in 2005 (Table 4).

Total accumulation of mineral components depended on the vegetation season, Zn treatments and the investigated element. In 2004, the Zn treatments significantly affected total uptake of N, Na, Ca and Mn, but in 2005 only of Zn. In 2004, sugar beet accumulated the highest amount of N at a level of 2.0 kg Zn/ha, but in 2005 on the control. On average for the two years, the Zn treatments significantly differentiated only Zn uptake. A significant difference was obtained between the accumulation of this component on the control plot and that fertilized with 1.5 Zn kg/ha (Table 5).

Table 5. Effect of zinc row application on nutrient uptake by sugar beet

Year	Zn rate	N	P	K	Na	Ca	Mg	Zn	Mn	Cu
	(kg/ha)	(kg/ha)						(g/ha)		
2004	0	204^{bc}	20.3	262	122^{b}	40.4^{ab}	41.9	389	778^{ab}	117
	0.5	154^{ab}	21.5	207	78^{a}	34.8^{a}	33.0	430	705^{ab}	95
	1.0	144^{a}	22.8	197	80^{a}	47.7^{b}	41.5	473	776^{ab}	109
	1.5	158^{ab}	20.9	195	79^{a}	41.1^{ab}	36.4	543	971^{b}	134
	2.0	212^{c}	22.1	235	96^{ab}	46.9^{b}	43.2	470	556^{a}	106
2005	0	228	24.8	286	108	58.7	68.5	306^{a}	930	95
	0.5	221	26.7	328	119	65.9	70.0	438^{b}	1037	97
	1.0	223	24.3	279	114	63.6	66.9	363^{ab}	1077	97
	1.5	225	22.9	282	123	77.0	70.0	378^{ab}	1106	124
	2.0	205	19.1	249	110	70.2	66.1	417^{b}	931	94
Mean	0	216	22.5	274	115	49.5	55.2	347^{a}	854	106
	0.5	188	24.1	268	98	50.4	51.5	434^{ab}	871	96
	1.0	184	23.6	238	97	55.7	54.2	418^{ab}	926	103
	1.5	192	21.9	239	101	59.1	53.2	460^{b}	1039	129
	2.0	208	20.6	242	103	58.5	54.6	444^{ab}	744	100

Homogeneous groups of treatments (for α = 0.05)

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The relationship between Zn accumulation and WSY was year depended (Table 4). The reason is due to a different content of available Zn prior the trial set up.

In conclusion, the concurrent application of Zn and N in the rows of sown seeds positively affect the yield and quality of sugar beet. Optimal for beet yield fertilizer rate was 2.0 kg Zn/ha, and for raw material quality it was 0.5 kg Zn/ha. The main reason of positive Zn activity should be seen in its impact on dry matter distribution and technological quality of storage roots.

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Corresponding author:

Dsc. Przemysław Barłóg, Ph.D., University of Life Sciences, Department of Agricultural Chemistry and Environmental Biogeochemistry, Wojska Polskiego 71F, 60 625 Poznan, Poland
e-mail: przembar@up.poznan.pl