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ORIGINAL PAPERS

SODIUM AS AN ELEMENT INCREASING NITROGEN PRODUCTIVITY – A CASE STUDY ON SUGAR BEET

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Abstract

The objective of the study was to evaluate the effect of sodium-enriched nitrogen fertilizers against the background of pre-sowing sodium fertilization on sugar beet productivity, including technological quality of taproots. A field experiment, completed in 2001-2003, consisted of two main factors: (i) pre-sowing sodium application (0, 30 kg Na ha^{-1} in the form of NaCl), (ii) a set of nitrogen fertilizing variants, composed of two sub-levels: one consisting of four nitrogen rates (0, 90, 120, 150 kg N ha^{-1}) and the other one comprising three chemical N fertilizer forms [(i) ammonium nitrate, 34%, AN, (ii) mixture of ammonium and sodium nitrates, 26%N + 6% Na (ASN1), (iii) mixture of ammonium and sodium nitrates, 21%N + 13% Na (ASN2)]. Depending on a nitrogen rate, the fertilizers were applied on two or three dates. The first N rate was applied only as ammonium nitrate. The in-season application of nitrogen and sodium as the 2nd and the 3rd rate of nitrogen allowed for discrimination of sodium rates, ranging from 0 to 44.2 kg Na ha^{-1}. The effect of soil applied sodium was significant in the 2nd and 3rd year of study. The highest yields of taproots and sugar, despite changeable weather conditions, were harvested on the 120 kg N ha^{-1} treated plot. The response of sugar beet plants to in-season applied sodium was varied and depended on soil available sodium content and the course of weather during the growing season. The strongest response occurred in 2003, characterized by both the lowest amount of available soil sodium and shortage of water. The necessity of sodium application, as a nutritional factor increasing yields of taproots and sugar, was clearly demonstrable under low soil sodium content (< 5 mg kg^{-1} soil). Then, the optimum rate of in-season applied Na in the form of ASN1 ranged from 14.8 to 29.5 kg Na ha^{-1}. The available sodium content, from 10 to 12 mg kg^{-1} soil, defined the upper limit of sodium fertilizer application. At that sodium fertility level, 7.4 kg Na ha^{-1} should not be exceeded. The highest unit N productivity, as attributed to the 90 kg N ha^{-1} treatment, responded positi-

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vely to soil and in-season applied sodium. Therefore, it can be concluded that soil and/or in-season applied sodium can improve productivity of unit nitrogen, provided that a nitrogen rate will be reduced by up to 30 kg N ha^{-1} in comparison to its optimum rate.

Key words: nitrogen rates, sodium nitrate, NaCl, sugar yield, nitrogen productivity.

SÓD JAKO PIERWIASTEK ZWIĘKSZAJACY PRODUKCYJNOŚĆ AZOTU – NA PRZYKŁADZIE BURAKA CUKROWEGO

Abstrakt

Celem badań była ocena wpływu nawozów azotowych wzbogaconych w sód na tle przedsiewnego nawożenia sodem na produkcyjność buraków, włącznie z jakością technologiczną korzeni. Eksperyment polowy (w latach 2001-2003) zawierał dwa czynniki nawozowe: (i) przedsiewne stosowanie sodu (0 i 30 kg Na ha^{-1}, w formie NaCl), (ii) zestaw wariantów azotowych, ujętych w dwa podpoziomy. Pierwszy, wyznaczony przez dawki azotu (0, 90, 120 i 150 kg N ha^{-1}), oraz drugi, wynikający ze składu chemicznego testowanych nawozów [(i) (saletra amonowa, 34% N (AN), (ii) mieszanina saletry amonowej i sodowej, 26% N + 6%Na (ASN1), (iii) mieszanina saletry amonowej i sodowej, 21% N + 13% Na (ASN2)]. W zależności od dawki azotu, nawozy stosowano w dwóch lub trzech terminach. Pierwszą dawkę azotu, przedsiewnie, stosowano tylko w formie saletry amonowej. Nawozy azotowe stosowane w drugiej i trzeciej dawce zawierały również sód. W ten sposób zróżnicowano pogłówne dawki sodu w zakresie od 0 do 44,2 kg Na ha^{-1}. Wpływ doglebowo zastosowanego sodu był istotny w drugim i trzecim roku badań, prowadząc do wzrostu plonu korzeni i cukru. Największy plon korzeni i cukru, niezależnie od warunków pogodowych, otrzymano stosując 120 kg N ha^{-1}. Reakcja buraka cukrowego na pogłówne nawożenie sodem była zmienna, warunkowana dostępnością tego składnika w glebie oraz przebiegiem warunków pogodowych. Największy przyrost plonu korzeni zanotowano w 2003 roku. Stwierdzono wówczas najmniejszą zawartość przyswajalnego sodu w glebie oraz niedobór wody w okresie wegetacji. Konieczność stosowania sodu jako czynnika żywieniowego zwiększającego plony korzeni i cukru ujawniła się jednoznacznie w stanowiskach ubogich w przyswajalny sód (<5 mg Na kg $gleby^{-1}$). W tych warunkach optymalna dawka sodu w formie ASN1 wynosiła od 14,8 do 29,5 kg Na ha^{-1}. Zawartość przyswajalnego sodu w glebie od 10 do 12 mg Na kg^{-1} wyznaczała górny poziom stosowania nawozów sodowych. W tym zakresie wielkość pogłównej dawki sodu nie powinna przekraczać 7,4 kg Na ha^{-1}. W wariancie z 90 kg N ha^{-1}, charakteryzującym się największą produkcyjnością jednostkową azotu, odnotowano wzrost tego wskaźnika w reakcji na doglebowe i pogłówne stosowanie sodu. Można więc stwierdzić, że doglebowe i pogłówne nawożenie buraka cukrowego sodem prowadzi do zwiększenia produkcyjności jednostkowej azotu. Warunkiem koniecznym jest redukcja dawki tego składnika nawet o 30 kg N ha^{-1} w porównaniu z dawką optymalną uzyskaną w warunkach bez nawożenia sodem.

Słowa kluczowe: dawki azotu, saletra sodowa, NaCl, plon cukru, produktywność azotu.

INTRODUCTION

Despite many potential ways to use sugar beet, including production of bio-ethanol or bio-gas, in Europe this crop is predominantly grown to produce sugar (MÄRLANDER et al. 2003, VENTURI, VENTURI 2003). Harvested yields of sugar depend on many natural and agro-technical factors, including weather conditions during the growing season. According to FRECLETON et al. (1999), the weather is responsible for 26% to 79% of yield variability. Drought in summer months (July and August) can be most detrimental to the final yield of beets. Nevertheless, the negative impact of water shortage on the growth of beet plants and sugar yield can be partly compensated for by a highly sophisticated fertilization system, in which required nutrients, their rate and application timing are managed properly (MÄRLANDER et al. 2003).

Potassium and sodium play the most important role in controlling the response of sugar beet plants to water shortage (GRZEBISZ et al. 2002). The effect of sodium on plants' growth and yielding has long been a subject of scientific controversy (RÖMER et al. 2004). The key biological and physiological functions of this element in sugar beet plants are related to its ability to replace potassium in its ordinary functions. A classical example of its physiological impact is regulation of the cell's osmotic potential and turgor (SUBBARAO et al. 2003). Contribution of potassium ions to the cell's total osmotic potential, depending on the plant type, ranges from 53 to 96%. It is well recognized that importance of other nutrients such as calcium, magnesium and especially sodium increases when potassium deficit appears. Plants classified as halophytes compensate high external osmotic pressure by accumulating sodium ions in the vacuole (FLOWERS 1985). It is supposed that this mechanism also works in sugar beet plants. Using data from hydroponics experiments with fodder beets, SUBBARAO et al. (1999) showed that sodium may replace up to 96% of the impact produced by potassium on the cell's osmotic potential. Therefore, sugar beet plants supplied with sodium instead of potassium do not show symptoms of potassium deficiency (WAKEEL et al. 2009). Experiments conducted under water stress have revealed an increased content of sodium in older leaves of sugar beet plants, which elevates the rate of photosynthesis (NIAZI et al. 2000). It is supposed that beet plants under water stress but well supplied with sodium are able to transport potassium to the most physiologically sensitive organs. Therefore, these findings raise a question about the impact of sodium on sugar beet productivity under conditions of water shortage in summer months.

One of the biggest controversies is stirred by the impact of sodium on nitrate transport within the plant. Although potassium is a key nutrient responsible for transport of nitrates in plants, sodium ions can increase their accumulation in sugar beet plants. The same phenomenon has been observed in the case of sulphate and chloride ions (SUBBARAO et al. 2003, HOFFMANN 2005). These findings underline the importance of sodium in controlling nitrogen use efficiency.

Sugar beet fertilization with sodium raises some doubts among agronomists regarding its optimum rates and effect on the quality of taproots and on sugar yield. In many scientific reports and papers, positive effects of sodium are demonstrated (HANSEN 1994, FRECLETON et al. 1999, WAKEEL et al. 2010). Some other reports underline the lack of response or even negative influence on taproot quality (VON BRAUNSCHWEIG 1983, MILFORD et al. 2000, RÖMER et al. 2004).

The key objective of this study was to assess the effect of sodium applied to soil as pre-sowing fertilization and/or in the form of mixtures of ammonium and sodium nitrates on nitrogen use efficiency, considered as a prerequisite of good yields of taproots and sugar.

MATERIAL AND METHODS

Field investigations were conducted during three consecutive seasons: 2001, 2002, 2003, on a farm in Sadki (Poland: 52°08'N; 16°47'E). The experimental design comprised two factors, as follows:

1) soil applied sodium: 0, 30 kg Na ha^{-1} (as NaCl);
2) a set of nitrogen fertilizing variants, composed of two sub-levels: one consisting of four rates of nitrogen fertilization (0, 90, 120 and 150 kg N ha^{-1}) and the other one comprising three types of nitrogen fertilizers: (i) ammonium saltpeter (AN), (ii) mix of ammonium and sodium nitrate, 26% N + 6%Na (ASN1), (iii) mix of ammonium and sodium nitrate, 21% N + 13%Na (ASN2).

The basic rate of sodium was applied two weeks before sugar beet sowing. The first N rate of 60 kg N ha^{-1} in the form of pure ammonium nitrate was applied before sugar beet sowing. The remaining rates of nitrogen fertilizers, enriched with sodium, were applied in accordance to the experimental design, at BBCH 14/16 and BBCH 19/37 stages of sugar beet (according to Meier et al. 2001). The composition of 10 nitrogen variants was as follows: control – without nitrogen (0), $60_{AN}+30_{AN}$ (AN_{90}); $60_{AN}+30_{ASN1}$ ($ASN1_{90}$); $60_{AN}+30_{ASN2}$ ($ASN2_{90}$); $60_{AN}+60_{AN}$ (AN_{120}); $60_{AN}+60_{ASN1}$ ($ASN1_{120}$); $60_{AN}+60_{ASN2}$ ($ASN2_{120}$); $60_{AN}+60_{AN}+30_{AN}$ (AN_{150}); $60_{AN}+60_{ASN1}+30_{ASN1}$ ($ASN1_{150}$); $60_{AN}+60_{ASN2}+30_{ASN2}$ ($ASN2_{150}$). The rates of sodium applied together with nitrogen were different, depending on the composition of the carrier, i.e., type of nitrogen fertilizer. For ASN1, sodium rates were it 7.4, 14.8 and 22.1 kg Na ha^{-1} and for ASN2 they were 14.8, 29.5 and 44.2 kg Na ha^{-1}.

The area of each treatment, replicated four times, was 54 m^2 (10 m × 12 rows). Field trials were established on fields cropped with spring barley in the preceding year. Post harvest residues of the cereal and white mustard, grown as green manure, were the only sources of the introduced organic matter. Phosphorus and potassium were applied, irrespective of the treatment, in rates of 21 kg P ha^{-1} (single super-phosphate, 19% P_2O_5 i 0,2% B), and 100 kg K ha^{-1} (muriate of potash, 60% K_2O).

The soil under the experiment was typical soil in Poland. It developed from glacial loamy sands, was poor in organic matter but rich in basic macronutrient. Its fertility declined in the order: 2001 > 2002 > 2003. The content of available sodium also decreased in that order. The amount of mineral nitrogen (N_{min} = N-NH_4 + N-NO_3), measured down to 60 cm, was high (Table 1).

Table 1

Physical and chemical properties of soil

Year	Soil layer (m)	Clay (g kg^{-1})	Corg (g kg^{-1})	pH_{KCl}	P*	K*	Mg**	Na**	Nmin*** (kg ha^{-1})
					(mg kg^{-1})				
2001	0.0-0.3	80	9.2	7.4	132	231	40	10.2	98
	0.3- 0.6	140	5.3	7.3	77	196	40	12.0	114
2002	0.0- 0.3	30	8.1	6.9	141	173	53	5.0	65
	0.3- 0.6	110	3.8	6.6	41	107	66	4.2	67
2003	0.0- 0.3	40	6.7	7.0	97	147	45	3.5	96
	0.3- 0.6	110	2.5	6.0	41	97	44	2.5	78

Extracting solution: *lactate buffer, pH 3.55; **0.0125 mol $CaCl_2$; ***0.01 mol $CaCl_2$.

The weather conditions during the study showed high year-to-year variability. The total of precipitations (in mm) from April to October was: 553 in 2001, 633 in 2002 and 412 in 2003. With respect to rainfall, the worst situation occurred in 2003. The total amount of rainfall in August and September 2003 was just 40 mm, while the required amount of water is estimated at 145 mm. In 2001 and 2002, the sum of precipitation in August and September was 150 and 169 mm, respectively, which satisfied the crop's water requirement.

Sugar beet plants were harvested at the technological maturity growth stage (BBCH 49) in the first decade of October from 16.20 m^2 (six rows per 6 m). The technological value of taproots, such as sugar content polarization (S), α-amino-N (α-N), potassium (K) and sodium (Na), were determined using a Venema auto-analyzer (Type IIG). Sugar concentration was determined in extracts (0.3% aluminium sulphate) by using the polarimetric method; K and Na were assayed photometrically and α-N was determined fluorimetrically with o-phthaldehyde (OPA). These basic characteristics of taproots were then used to calculate some technological indices such as (BUCHHOLZ 1995):

1) standard molasses loss, SML = 0.12 · (K+Na) + 0.24 · α-N + 1.08 (%);
2) recoverable sugar, RS = S – SML (%);
3) processing efficiency (recovery), PE = (100 · RS) · S^{-1} (%);
4) recoverable (white) sugar yield, $Y_S = (Y_B \cdot RS) \cdot 100^{-1}$ (t ha^{-1});

where: K – content of potassium in mmol 100^{-1} g of fresh taproots; Na – content of sodium in mmol 100^{-1} g of fresh taproots; α-N – content of α-amino-N in mmol 100^{-1} g of fresh taproots; Y_B – beet (taproots) yield in t ha^{-1}; S – polarimetric determined sugar content in beet in %.

The efficiency of N fertilizer was evaluated using two classical parameters:

1) partial factor productivity nitrogen, PFP_N:

$$PFP_N = \frac{YS}{DN} (\text{kg kg}^{-1});$$

Table 2

Effect of sodium chloride fertilization on sugar beet yield

Year	Treatment	Taproots yield (t ha^{-1})	Leaves yield (t ha^{-1})	Taproots/leaves ratio
2001	- Na	64.1^{a}	32.7^{a}	0.52^{a}
	+ Na	64.4^{a}	30.4^{a}	0.48^{a}
2002	- Na	53.7^{a}	23.2^{a}	0.43^{a}
	+ Na	56.4^{b}	25.1^{b}	0.45^{a}
2003	- Na	51.0^{a}	23.9^{a}	0.47^{a}
	+ Na	56.1^{b}	25.0^{a}	0.44^{a}
Mean	- Na	56.2^{a}	26.6^{a}	0.47^{a}
	+ Na	59.0^{b}	26.8^{a}	0.46^{a}

Means with the same letter are not significantly different at α=0.05 (Tukey's test).

2) agronomic efficiency of fertilizer, AE_N:

$$AE_N = \frac{YS(N) - YS(0)}{DN} (\text{kg kg}^{-1});$$

where: Y_S = white (recoverable) sugar yield (kg ha^{-1}); $Y_{S(N)}$ and $Y_{S(0)}$ – white sugar yield with and without N-fertilization (kg ha^{-1}); D_N – rate of N (kg ha^{-1}).

All sets of collected data were subjected to analysis of variance (Fisher-Snedocor's method) for each year separately and for the interaction between year and experimental treatment, using computer software Statistica 9. In the calculation procedure (analysis of variance), the nitrogen fertilizer rates and chemical composition of tested fertilizers were considered as levels of the same factor. For F-test showing significant differences, Tukey's test (HSD) at the probability level of α = 0.05 was additionally performed to compare mean values. Stepwise variable selection was performed in order to find out relationships between white sugar yield and other parameters.

RESULTS AND DISCUSSION

The three-year average values implicitly indicate that pre-sowing application of sodium in the rate of 30 kg Na ha^{-1} is a measure which increases yields of sugar beets and recoverable sugar. The yield stimulating effect of this nutrient was in fact achieved though an increase in the taproot yield. A significant yield increase was found in two of the three years. In 2002, the relative increase was about 5% ($p \leq 0.018$), but in 2003 it went up to 10% ($p \leq 0.001$). In the third year, the yield was reduced due to shortage of water in August and September, as mentioned above. Yields of tops and taproot to top ratios did not show any response to soil applied sodium despite the year-to-year weather variability (Table 2). The same trend in the response of sugar beet to sodium application has been observed by Haneklaus et al. (1998).

Table 3

Taproot and leaf yields depending on the rate and chemical composition of in-season applied N-fertilizer; means for treatments with and without NaCl fertilization (t ha^{-1})

Treatment	Taproots yield				Leaves yield			
	2001	2002	2003	mean	2001	2002	2003	mean
0	59.5 ^{a}	45.4 ^{a}	51.3 ^{a}	52.1 ^{a}	27.8 ^{a}	18.1 ^{a}	19.5 ^{a}	21.8 ^{a}
AN$_{90}$	62.5 ^{ab}	54.4 ^{b}	51.9 ^{ab}	56.2 ^{ab}	28.4 ^{a}	24.0 ^{ab}	25.3 ^{abc}	25.9 ^{ab}
ASN1$_{90}$	67.7 ^{ab}	57.3 ^{b}	51.6 ^{ab}	58.9 ^{b}	34.7 ^{a}	27.9 ^{b}	23.0 ^{ab}	28.5 ^{b}
ASN2$_{90}$	65.5 ^{ab}	57.0 ^{b}	54.9 ^{ab}	59.2 ^{b}	31.7 ^{a}	22.0 ^{ab}	25.1 ^{abc}	26.3 ^{ab}
AN$_{120}$	67.9 ^{b}	52.8 ^{ab}	55.5 ^{ab}	58.8 ^{ab}	32.8 ^{a}	22.9 ^{ab}	23.5 ^{ab}	26.4 ^{ab}
ASN1$_{120}$	64.6 ^{ab}	58.9 ^{b}	57.7 ^{b}	60.4 ^{b}	30.3 ^{a}	27.8 ^{b}	29.8 ^{c}	29.3 ^{b}
ASN2$_{120}$	62.3 ^{ab}	59.6 ^{b}	57.2 ^{ab}	59.7 ^{b}	32.0 ^{a}	25.5 ^{b}	26.7 ^{bc}	28.1 ^{b}
AN$_{150}$	65.9 ^{ab}	52.3 ^{ab}	51.9 ^{ab}	56.7 ^{ab}	33.6 ^{a}	24.1 ^{ab}	23.5 ^{ab}	27.1 ^{ab}
ASN1$_{150}$	64.4 ^{ab}	56.7 ^{b}	51.0 ^{ab}	57.4 ^{ab}	33.3 ^{a}	25.9 ^{b}	22.3 ^{ab}	27.2 ^{ab}
ASN2$_{150}$	62.4 ^{ab}	55.6 ^{b}	52.5 ^{ab}	56.8 ^{ab}	31.1 ^{a}	23.2 ^{ab}	25.4 ^{abc}	26.6 ^{ab}

Means with the same letter are not significantly different at a=0.05 (Tukey's test).

Positive effect of sodium application on sugar beet yield can be partly explained by differences in the soil available content of both potassium and sodium. In 2001, the content of both nutrients was high, providing good conditions for supply of both nutrients. The content of soil available potassium above 20 mg kg^{-1} soils is a prerequisite for a high rate of sugar beet growth and yielding (Wojciechowski et al. 2002). Absence of any response of sugar beet to an available sodium content above 10 mg kg^{-1} soil could be used as an indicator of soil sodium self-sufficiency. Moderate response, as found in 2002, and strong response in 2003 are related to an insufficient content of available soil sodium and to the shortage of water that occurred in 2003. These results are in agreement with those reported by Drycott, Durrant (1976). There are some reports underlying increasing adaptability of sugar beet plants to prolonged drought, provided that they are well supplied with sodium (Bloch et al. 2006). Some authors stress that sodium is much more effective in preventing the negative response of sugar beet to water shortage than potassium (Drycott, Durant 1976, Hampe, Marschner 1982).

The effect of nitrogen treatments on sugar beet yields was significant in all the three years at $p \leq 0.0447$, $p \leq 0.00014$ and $p \leq 0.022$ in 2001, 2002 and 2003, respectively (Table 3). In the present study, no significant interaction has been found for the NaCl x N-treatments. The assessment of the response of sugar beet to the applied nitrogen fertilizers involves first of all an evaluation of the yields harvested on the control plot, i.e. without any addition of external nitrogen. As presented in Table 1, the general level of soil fertility was high, allowing high efficiency of soil mineral nitrogen (N_{min}), as presented below for the harvested quota of taproots (Y_B):

$$Y_B = 0.176N_{min} + 21.74 \quad \text{for } R^2 = 0.99 \text{ and } n = 3, p = 0.001,$$

where: Y_B – taproot yield, t ha^{-1}; N_{min} – mineral nitrogen, kg N ha^{-1} in the soil layer 0-0.6 m.

Therefore, any differences between the control plot and experimental treatments can be explained by the composition of nitrogen fertilizers and weather in each of the growing seasons. In 2001, the highest yield of taproots was harvested from the plot fertilized with 120 kg N ha^{-1} in the form of AN (Table 3). However, in comparison to the control plot, this increase was only 14%. A positive effect but not a significant one was attributed to sodium only when applied in the 90 kg N ha^{-1} treatment. A higher rate of nitrogen caused a slight yield decrease, but there are different explanations. Some authors relate yield decrease to an antagonism between sodium and other cations – calcium, magnesium (WAKEEL et al. 2009). In 2002, the highest yield of taproots was recorded in the plot fertilized with 120 kg N ha^{-1}, but applied as ASN2. The relative yield increase compared to the control plot was high, slightly above 30%. However, the same level of yield was attributed both to all 90 kg N ha^{-1} treatments and to 150 kg N ha^{-1} treatments with sodium. These data clearly indicate that sodium application to soil poor in this nutrient can rise significantly yields of both taproots and tops. In the third year (2003), characterized by excessive water shortage in the late season, the highest yield increase versus the control was attributed to the treatment consisting of 120 kg N ha^{-1} and ASN1 fertilizer. The yield averaged over years verifies the significant impact of sodium applied during the season, irrespective of the year-to-year variability. The highest yield of taproots was recorded in the treatment fertilized with 120 kg N ha^{-1} in the form of ASN1 (Table 3). However, the same level of yield was noted for the 90 kg N ha^{-1} in the form of ASN1 or ASN2 and for the 120 kg N ha^{-1} in the form of ASN2 ($p \leq 0.0011$). It can be concluded that the optimum rate of sodium applied in the season ranges from 14.8 to 29.5 kg Na ha^{-1}. This amount of sodium should be recommended on soil generally poor in sodium. The results suggest that it is necessary to substitute, even partly, some ammonium saltpeter by sodium nitrate (HENKENS 1971). In contrast, on soil reach in sodium, the effect of applied sodium nitrate can be controversial, as pointed out by ALLISON et al. (1994).

This study showed distinctly that the technological quality of taproots depends to a great extent on the course of weather during the growing season and on applied N rates (Table 4). Both factors had the strongest effect on the concentration of sugar and nitrogen compounds (α-N). At the same time, these two taproot quality indicators showed a contrary response to the annually changing weather conditions. Variation in the potassium and sodium concentrations was much lower. Sodium applied to soil did not affect taproot quality, thus indirectly revealing its positive impact on sugar beet growth. A complex qualitative parameter called sugar loss achieved a much higher value in 2002 than in the other two years. Its variation was in accordance with changes in the concentration of α-N compounds (Table 4).

Sophisticated management of nitrogen on a sugar beet plantation should take into account three aspects: (i) N fertilizer rate, (ii) N application tim-

Table 4

Response of sugar beet quality to experimental factors

Year and levels of treatments	Quality parameters					
	polarization S (%)	a-N (mmol kg^{-1})	K (mmol kg^{-1})	Na (mmol kg^{-1})	loss SML (%)	recovery PE (%)
Year						
2001	17.65 ^{a}	23.4 ^{b}	40.2 *a*	3.5 ^{a}	2.16 ^{a}	87.8 ^{ab}
2002	17.78 ^{a}	24.1 ^{b}	51.9 ^{ab}	5.4 ^{b}	2.33 ^{b}	86.9 ^{a}
2003	20.53 ^{b}	19.0 ^{a}	57.8 ^{b}	4.4 ^{ab}	2.27 *ab*	88.9 ^{b}
NaCl- fertilization						
- Na	18.56 ^{a}	22.5 ^{a}	49.1 ^{a}	4.4 ^{a}	2.25 ^{a}	87.8 ^{a}
+ Na	18.75 ^{a}	21.9 ^{a}	50.9 ^{a}	4.5 ^{a}	2.26 ^{a}	87.9 ^{a}
Treatments of N-fertilization						
0 (without N)	19.34 ^{c}	15.3 ^{a}	46.6 ^{a}	3.7 ^{a}	2.04 ^{a}	89.4 ^{b}
AN$_{90}$	18.89 ^{abc}	21.2 ^{ab}	48.4 ^{a}	4.3 ^{a}	2.21 ^{ab}	88.2 ^{ab}
ASN1$_{90}$	18.60 ^{ab}	23.3 ^{ab}	50.8 ^{a}	4.1 ^{a}	2.28 ^{ab}	87.6 ^{a}
ASN2$_{90}$	18.68 ^{abc}	20.7 ^{ab}	50.4 ^{a}	4.7 ^{a}	2.22 ^{ab}	88.0 ^{ab}
AN$_{120}$	18.82 ^{abc}	19.8 ^{ab}	50.2 ^{a}	3.7 ^{a}	2.19 ^{ab}	88.3 ^{ab}
ASN1$_{120}$	18.60 ^{ab}	21.5 ^{ab}	49.8 ^{a}	4.4 ^{a}	2.23 ^{ab}	88.0 ^{ab}
ASN2$_{120}$	18.58 ^{ab}	22.6 ^{ab}	50.1 ^{a}	5.2 ^{a}	2.27 ^{ab}	87.7 ^{a}
AN$_{150}$	18.47 ^{ab}	26.8 ^{b}	50.0 ^{a}	4.5 ^{a}	2.36 ^{b}	87.1 ^{a}
ASN1$_{150}$	18.40 ^{ab}	25.7 ^{b}	53.8 ^{a}	5.3 ^{a}	2.39 ^{b}	87.0 ^{a}
ASN2$_{150}$	18.16 ^{a}	24.7 ^{b}	49.8 ^{a}	4.8 ^{a}	2.31 ^{b}	87.2 ^{a}

Means with the same letter are not significantly different at a=0.05 (Tukey's test).

ing during the growing season, (iii) N fertilizer chemical composition. As a rule, all of these factors are important for recoverable sugar yield (Märlander et al. 2003). This general observation is fully supported by the present study. Nevertheless, the effect of nitrogen on taproot quality was to some extent modified by applied sodium. Some key indicators of beet quality such as sugar and α-N concentration showed a strong but contrary response to increasing N rates. The effect of applied sodium on sugar concentration was generally negative, decreasing in accordance with the increasing rates of both N and Na. Plants fertilized with the highest N rate showed a very high concentration of α-N compounds, which showed a tendency to decrease in response to external supply of sodium (Table 4). Concentration of potassium and sodium, in spite of raising rates of both nitrogen and sodium, did not show any significant changes. However, it has been observed a serious impact of both nitrogen and sodium fertilizers on sodium concentration in taproots. Some qualitative parameters such as loss of sugar and sugar recovery showed a higher response to N than to sodium rates. At the same time, both parameters were inversely related to changes in α-N concentration. The obtained results are not in agreement with a thesis presented by Hanekluas et al. (1998), who underline positive aspects of sodium application on sugar beets yield but at the same negative on taproots quality.

Yield of recoverable sugar is considered as a product of yield of taproots and their qualitative characteristics. This study showed that yield of taproots explained 60%, 86% and 92% of sugar yield variability in 2001, 2002, 2003, respectively (Table 5). This simple comparison fully supports a hypothesis proposed by Hanekluas et al. (1998) about the dominating effect of sodium on taproot yield. However, analysis of the influence of these two yield forming components on sugar yield variability showed a much more complicated picture, as presented in Table 5. The two last equations (nos 11 and 12) indirectly indicate importance of sugar beet quality as a factor significantly responsible for both N and Na rates (Table 5).

On average, the highest yield of recoverable sugar, up to 9.95 t ha^{-1}, was harvested in 2001. Statistically, the same yield was recorded in 2003 (9.80 t ha^{-1}). Application of NaCl significantly influenced white sugar yield in 2002 and 2003 (Figure 1). In 2001, the effects of tested N-fertlizers were negligible, but addition of sodium, excluding the 90 kg N ha^{-1} treatment, showed negative impact on the harvested volume of sugar (Figure 2). Nevertheless, the plot fertilized with nitrogen in the form of ASN1 should be considered as interesting for future studies on nitrogen use efficiency in sugar beet. In 2003, characterized by a low content of soil available sodium and unfavorable growth conditions, sugar beet plants fertilized with 120 kg N ha^{-1} and sodium in the rate of 22.1 kg Na ha^{-1} produced the highest yield of sugar. In 2002, yields of sugar were much lower but the highest ones occurred in the treatment of 120 kg N and 14.8 kg Na ha^{-1}. In 2002, the relative sugar yield increase due to sodium application was 7.3%

Table 5

Recoverable sugar yield as a function of taproot yield, YB (t ha^{-1}) and sugar content, S (%) depending on the year and treatment of NaCl fertilization

No	Year	Equation	R^2 value	*n*
1.	2001	$Y_S = 1.841 + 0.1263\ Y_B$	$R^2 = 0.60^{**}$	$n = 20$
2.		$Y_S = -13.109 + 0.1556\ Y_B + 0.7400\ S$	$R^2 = 0.99^{**}$	$n = 20$
3.	2002	$Y_S = 0.4587 + 0.1460\ Y_B$	$R^2 = 0.86^{**}$	$n = 20$
4.		$Y_S = -12.171 + 0.1566\ Y_B + 0.6778\ S$	$R^2 = 0.99^{**}$	$n = 20$
5.	2003	$Y_S = -0.8850 + 0.1933\ Y_B$	$R^2 = 0.46^{**}$	$n = 20$
6.		$Y_S = -13.264 + 0.1719\ Y_B + 0.6744\ S$	$R^2 = 0.99^{**}$	$n = 20$
7.	mean	$Y_S = 3.2046 + 0.1077\ Y_B$	$R^2 = 0.46^{**}$	$n = 60$
8.		$Y_S = -10.886 + 0.1662\ Y_B + 0.5748\ S$	$R^2 = 0.99^{**}$	$n = 60$
9.	-Na treatments	$Y_S = 2.9766 + 0.1094\ Y_B$	$R^2 = 0.58^{**}$	$n = 30$
10.		$Y_S = -10.7837 + 0.1666\ Y_B + 0.5677\ S$	$R^2 = 0.99^{**}$	$n = 30$
11.	+Na treatments	$Y_S = 3.437 + 0.3339\ S$		$n = 30$
12.		$Y_S = -10.7779 + 0.1634\ Y_B + 0.5780\ S$	$R^2 = 0.99^{**}$	$n = 30$

*, ** – significant level for $p \leq 0.01$ and 0.001, respectively

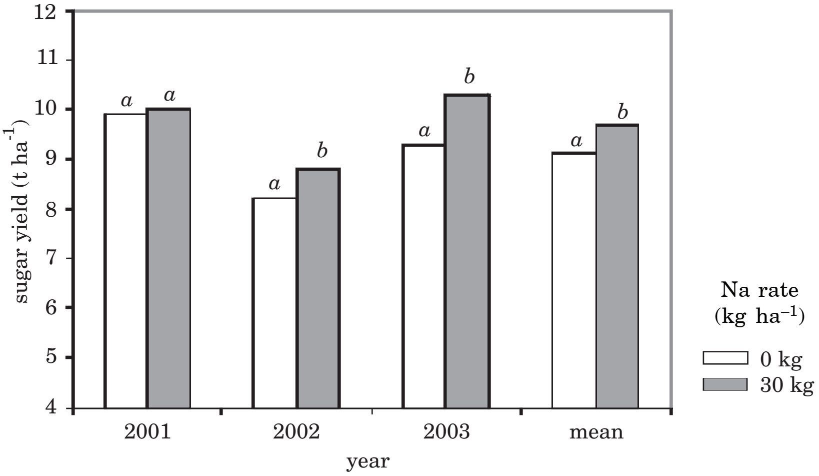

Fig. 1. Effect of NaCl fertilization on recoverable sugar yield (means for N-treatments). Means with the same letter are not significantly different at α=0.05 (Tukey's test)

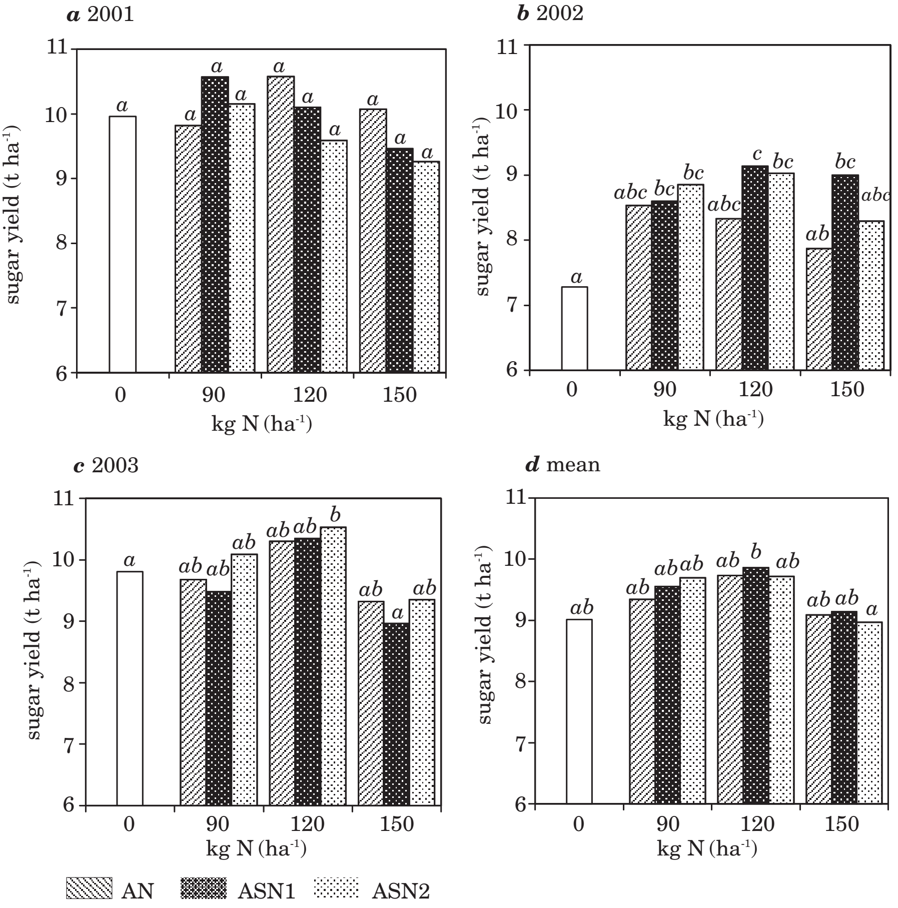

Fig. 2. Effect of nitrogen rate and type of fertilizers on recoverable sugar yield.
Means for treatments with and without NaCl fertilization.
Means with the same letter are not significantly different at α=0.05 (Tukey's test)

($p \leq 0.0013$), but in 2003 it rose to 10.7% ($p \leq 0.0001$). Yield of sugar, averaged over years and soil applied sodium, raised in accordance to the N rate up to 120 kg N ha^{-1} and Na rate up to 22.1 kg N ha^{-1} (Figure 2). These results suggest indirectly presence of N and Na interaction, which became evident only under relatively low N rates. The essential meaning of the above figures is higher productivity of applied N in the presence of sodium.

The interaction between nitrogen and sodium has been verified by using two indices, partial factor of nitrogen productivity (PFP$_N$) and net agronomic efficiency (AE$_N$). The first index describes unit nitrogen fertilizer productivity, which decreased significantly in response to increasing N rates but at the same time increased in response to soil applied sodium (Table 6).

Table 6

Response of indices of nitrogen fertilizer efficiency to in-season applied nitrogen and sodium (means for the years 2001-2003)

Treatment of fertilization	Partial factor productivity, PFPN (kg kg^{-1})			Agronomic N efficiency, AEN (kg kg^{-1})		
	-Na	+Na	mean	-Na	+Na	mean
AN_{90}	98.1	109.5	103.8 ^{a}	2.4	4.9	3.6 ^{a}
$ASN1_{90}$	102.4	109.7	106.1 ^{a}	6.7	5.1	5.9 ^{a}
$ASN2_{90}$	105.7	109.8	107.8 ^{a}	10.0	5.2	7.6 ^{a}
AN_{120}	80.0	82.3	81.2 ^{b}	6.4	0.2	3.3 ^{a}
$ASN1_{120}$	83.1	81.3	82.2 ^{b}	11.3	2.8	7.1 ^{a}
$ASN2_{120}$	78.9	83.0	81.0 ^{b}	7.1	4.6	5.9 ^{a}
AN_{150}	60.4	60.8	60.6 ^{c}	2.9	-2.0	0.5 ^{a}
$ASN1_{150}$	57.2	64.7	60.9 ^{c}	-0.2	1.9	0.8 ^{a}
$ASN2_{150}$	56.1	63.4	59.8 ^{c}	-1.3	0.6	-0.3 ^{a}
Mean	80.2 ^{m}	85.0 ^{n}	82.6	5.0 ^{m}	2.6 ^{m}	3.8

Means with the same letter are not significantly different at a=0.05 (Tukey's test).
Type of statistical differences: $m - n$ ® soil applied sodium; $a - c$ ® N × Na treatments

Explicit interaction between soil applied sodium and nitrogen treatments, also including sodium, has not been found. However, plants fertilized with sodium and 90 kg N ha^{-1} showed an increasing trend of unit N productivity, irrespective on broadcast applied sodium, The same positive trends are attributed to the 150 kg N treatment, but the PFP_N values were much lower. It could be therefore suggested that some of the applied nitrogen fertilizer can be successfully replaced by sodium. This hypothesis in illustrated in Figure 3, which shows that soil applied sodium allows one to decrease the optimum N rate by up to 30 kg ha^{-1}. The results are in agreement with the data reported by HANSEN (1994), who found that sodium applied in the rate of 60 kg Na ha^{-1} allowed a decrease in the optimum rate of fertilizer nitrogen from 120 to 80 kg N ha^{-1}. The other indicator of fertilizer N productivity, that is AE_N, did not show any response to the tested factors. However, the highest and positive trends should be attributed only to the 90 kg N ha^{-1} treatment (Table 6).

The study clearly revealed that the available sodium content (10-12 mg Na kg^{-1} soil) is sufficient to cover sugar beet requirements with respect to this element. However, a small rate of sodium up to 7.4 kg ha^{-1} (as sodium nitrate) can increase efficiency of applied nitrogen fertilizer, but the N rate should be reduced. Sugar beet plants cultivated under conditions of a low amount of soil available sodium should be fertilized, applying sodium fertilizers before sowing and during plant vegetation. The pre-sowing sodium

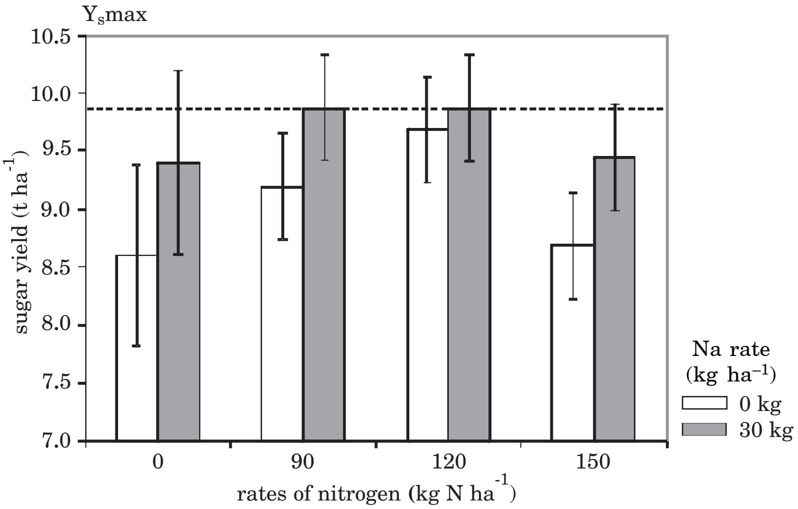

Fig. 3. Recoverable sugar yield response to N rates against the background of soil applied sodium (means for N-fertilizers). Vertical bars represent 0.95 confidence intervals at the α=0.05 level

application is a key factor affecting the N unit productivity, provided that N rates are significantly reduced. Under conditions dominating in Poland, a sodium rate should not be higher than 30 kg ha^{-1}.

CONCLUSIONS

1. The expected response of sugar beet and recoverable sugar yields to sodium fertilizers can be revealed only under conditions of low soil available sodium and water shortage during the growing season.

2. Response of qualitative characteristics of storage roots to sodium application is weak, showing a slight negative effect of sodium nitrate on sugar, but positive one on α-N concentration.

3. In-season application of fertilizer sodium can increase productivity of unit fertilizer nitrogen, but only under low amount of externally applied nitrogenous fertilizer.

4. The positive effect of soil applied sodium on nitrogen unit productivity is a basis for reduction in the nitrogen fertilizer rate in sugar beet production.

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