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SUGAR BEET RESPONSE TO BALANCED NITROGEN FERTILIZATION WITH PHOSPHORUS AND POTASSIUM PART III. DYNAMICS OF WHITE SUGAR YIELD DEVELOPMENT

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Abstract

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The main objective of the study was to evaluate the dynamics of white sugar yield (WSY) by beet crop under conditions of imbalanced application of key nutrients, such as P, K with respect to N. The field trial arranged as one-factorial design was consisted of eight treatments: $N_0P_0K_0$; $N_0P_1K_1$; $N_1P_0K_1$; $N_1P_1K_0$; $N_1P_{0.25}K_{0.25}$; $N_1P_{0.5}K_1$; $N_1P_1K_1$ and $N_1P_1K_1$+Ca; where 1 is recommended level of NPK fertilization and Ca means that phosphorus applied as partially acidulated phosphoric rock (PAPR). The harvest of sugar beet took place at following days after sowing (DAS): 92, 113, 134, 155 and 175. Yield of white sugar was determined by set of standard methods used in a sugar beet factory. The course of weather was the dominant factor, affecting realization of yielding potential of a crop on the background of supply of P and K. Under favorable growth conditions, yield of sugar increased accordingly with increasing rates of fertilizer P. Yield forming effect of P, as a rule, revealed in the late-season, resulting in the WSY increase of 30–40% at 175 DAS compared to 155 DAS. The average yield increase in response to optimal application of P was 18.4%, whereas of K only 6.0%. In years with drought, the effect of P was low due to limited development of the storage root to accumulate sucrose. The main reason was a probably insufficient supply of N and K in the mead-season, restricting size of the root. Consequently, the optimum P rate to harvest sufficiently high WSY in years with drought was at the level of 25% of the P recommended rate. On the average, the maximum yield of WSY was harvested in $N_1P_1K_1$+Ca treatment, indirectly indicating on an importance of Ca as a sugar yield forming nutrient.

*Key words***:** sugar yield, dynamics of sugar accumulation, nitrogen, phosphorus, potassium, imbalanced fertilization

Introduction

Sugar production is the main goal of sugar beet (*Beta vulgaris* L.) cultivation in Poland. The area under cropping is estimated to about 190×10^3 ha, with sugar production of 1.8×10^6 Mg per annum, hence Poland is classified as the leading sugar producer in Europe (FAOSTAT, 2012). According to Supit et al. (2010), yield potential of sugar beet in climatic regions extending from northern France through Germany to eastern Poland, is at the level of *ca* 11 Mg ha^{-1} (taking into account 80 Mg ha^{-1} of beets and white sugar recovery concentration of 14%). However, in France farmers harvest 86%, in Germany 68%, but in Poland from 50% to 60% of current yielding potential of sugar beet varieties. The key reasons of these differences are attributed to climatic conditions and soil fertility level. Soils in Poland originate from postglacial material, naturally poor in colloids. As results they are characterized by a low-water retention and natural shortage of nutrients, especially potassium (Grzebisz and Diatta, 2012). There should be also taken into account

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structure of nutrients applied in fertilizers. It is well documented that N is the nutrient most limiting beet productivity (Märländer at al., 2003; Hergert, 2010). The application of low N rates results in decreased root tonnage. However, too high rates of N leads to reduced sugar content and increased concentration of impurities, such as α-amino N, K and Na (Hoffmann, 2005; Hoffmann and Märländer et al., 2005).

The most important purpose of sugar beet growers is to increase N use efficiency. The success in this area depends not only on N concentration in soil, N rates, timing or methods of fertilizer application, but also on content of other nutrients in soil, especially of P and K (Wiebel and Orlovius, 1997; Nikolova, 1999; Römer et al., 2004; Barłóg et al. 2010). The imbalanced application of P and K with respect to the rate of N fertilizer disturbs growing conditions, considering both nutrients as factors in the minimum (Grzebisz et al., 2012). Fertilization with N in excess, leads to its accumulation in soil, in turn causing a negative pressure on the environment. Nowadays, N management is considered as one of the key challenges for both for researchers and farmers. It is the core of sustainable agricultural production in the 21st century (Eickhout et al., 2006; Tzilivakis et al., 2005).

The main aim of the conducted study was to evaluate the dynamics of white sugar production by sugar beet during the course of the growing season on the background of constant rate of fertilizer nitrogen and imbalanced rates of phosphorus and potassium.

Materials and Methods

The conducted study basis on data obtained from the field static experiment, which was carried out in private farm at Wieszczyczyn (52°02′N17°05′E) during three consecutive growing seasons 2001, 2002, 2003. The basic information about weather and soil condition the conducted experiments are described in details in the first part of this paper (Barłóg et al., 2013). A completely randomized experimental design was employed with four replications and area of 54 m^2 per plots. The field trial, arranged as one-factorial design, replicated four times, consisted of eight following treatments:

A. absolute control, i.e. no applied fertilizers (acronym $N_0P_0K_0$),

B. nitrogen control, 100% of recommended level of P and K ($N_0P_1K_1$),

C. phosphorus control, 100% of recommended level of N and K ($N_1P_0K_1$),

D. potassium control, 100% of recommended level of N and P ($N_1P_1K_0$),

E. 100% of recommended level of N but 25% of P and K ($N_1P_{0.25}K_{0.25}$),

F. 100% of recommended level of N and K but 50% of P ($N_1P_{0.5}K_1$),

G. 100% of recommended level of NPK ($N_1P_1K_1$),

H. 100% of recommended level of NPK, P applied as PAPR ($N_1P_1K_1$+Ca).

The recommended level of each nutrient in the successive years of study (2001/2002/2003) amounted to: 150/150/120 kg N ha^{-1}; 60/60/80 kg P_2O_5 ha^{-1} and 180/180/300 kg K_2O ha^{-1}. The rate of N, P, K was calculated both on agrochemical properties of soils and nutrient requirements of sugar beets yield at the level of 60 Mg × ha^{-1}. Phosphorus was applied as single superphosphate (20% P_2O_5), except $N_1P_1K_1$+Ca treatment – P was applied as 50% partially acidulated phosphoric rock (PAPR); potassium as muriate of potash (60% K_2O), and nitrogen as ammonium nitrate (34% N). Phosphorus and potassium fertilizers were applied in autumn, after the harvest of the fore-crop (winter wheat). Nitrogen was applied at two dates: i) before sugar beet sowing (60% of recommend levels) and ii) at the 4–6 leaf growth stage.

Sugar beet plants (Kassandra variety) were sampled at 92, 113, 134, 155 and 175th day after sowing (DAS) within an area of 3.6 m^2 and 7.2 m^2 at the last date. At each date the fresh root weight (FW) was determined and next a subsample was transferred to the factory's tare house for determination of the standard root quality characteristics, i.e. concentration of sucrose (SC), α-amino-N (AmN), K and Na on the FW basis. White sugar yield was calculated according to the Brunswick formula (Buchholz et al., 1995), using a set of following equations:

$$SML = 0.12\,(K + Na) + 0.24\,AmN + 1.08$$
$$WSC = SC - SML$$
$$WSY = (BY \times WSC)/100,$$

where SML is standard sugar molasses loss (%); K + Na is sum of potassium and sodium concentration in beet (mM 100 g^{-1} fresh matter); AmN is α-amino N concentration in beet (mM 100 g^{-1} fresh matter); SC is sucrose concentration (% on beet fresh matter); BY is yield of beet (Mg ha^{-1}); WSY is yield of white sugar (Mg ha^{-1}).

A two-way ANOVA was carried out to determine the effects of years (Y), NPK fertilization (F), years x fertilization (Y x F). The data set at 175 DAS was elaborated by using one-way ANOVA for each year separately. For F-test showing significant differences, Tukey's test (HSD) at the probability level α = 0.05 was additionally performed to compare mean values. The relationship between WSY and DAS was described with the linear regression model. The multiple regression and stepwise variable selection were used to evaluate relationships between WSY and beet yield (BY) and its quality parameters.

Results

The yield of white sugar (WSY) was a result of interaction of year and fertilizing treatments. The course of weather during beet vegetation was the dominant factor. Its yield forming effect revealed, however, as the year-dependent expression of a particular NPK treatment. Therefore, effects of fertilizing variants on dynamics of WSY development throughout the growing season was evaluated for years, averaged over treatments, and treatments averaged over years (Table 1).

Table 1

Effect of years and balanced NPK fertilization on white sugar yield (WSY); F ratios of two-way analysis of variance

Factors	df	Days after sowing (DAS)				
		92	113	134	155	175
Years (Y)	2	58.1***	65.8***	195.2***	86.5***	156.7***
Fertilization (F)	7	23.0***	25.7***	18.9***	28.1***	24.3***
Interaction Y x F	15	5.4***	6.5***	6.4***	8.9***	5.4***

*, **, *** significant level for $P \leq 0.05$; 0.01; 0.001, respectively

Effect of years, as the most important component of temporary and final WSY, showed high in-season variability (Table 2). In 2001, at 92 DAS, it was by 40% higher compared to other two years average. Its subsequent increase, based on in a three-weekly period, was almost constant, ranging from 2.2 to 2.6 Mg ha^{-1}. In 2002, with water shortage, the rate of WSY in-growth in respective periods was much lower, ranging from 1.7 to 2.0 Mg ha^{-1}. In the third season, 2003, also dry, the critical for final yield of sugar was the mead-season, with temporary yields below those in 2001. This trend changed in the late-season, as indicated by the yield increase of more than 3.0 Mg ha^{-1} per a respective period from 134 DAS onwards. The key reason of the WSY increase was a high SC, which averaged over treatments, was at the level of 19% (Barłóg et al., 2014).

Effect of fertilizing treatments, averaged over years, was sampling date-specific. At 92 DAS, the tested treatments can be divided into homogenous several groups, but the only N control treatments showed by 50% or 75% lower WSY as compared to imbalanced or fully balanced treatments, respectively. At 113 DAS, yields of sugar doubled for most of the treatments. Slightly lower increase was noted for $N_1P_0K_1$, $N_1P_{0,5}K_1$ and $N_1P_1K_1$+Ca. At the same time the highest WSY increase, excluding the absolute control ($N_0P_0K_0$), was noted for $N_1P_{0.25}K_{0.25}$. In the third three-weekly period, WSY increase was much lesser (*ca* 40%) compared to the previous one, but in some treatments, a compensation response was noted. In the fourth period three highly homogenous groups,

Table 2

Dynamics of white sugar yield (WSY) development in dependence on years and fertilizing treatments (Mg ha^{-1})

Factor	Days after sowing (DAS)				
	92	113	134	155	175
Year					
2001	2.8 ^{b}	5.0 ^{c}	7.6 ^{c}	9.9 ^{c}	12.5 ^{b}
2002	1.9 ^{a}	3.6 ^{a}	5.3 ^{a}	7.1 ^{a}	9.1 ^{a}
2003	2.1 ^{a}	4.4 ^{b}	5.9 ^{b}	9.0 ^{b}	12.3 ^{b}
Treatment					
$N_0P_0K_0$	1.4 ^{a}	3.1 ^{a}	4.5 ^{a}	5.9 ^{a}	9.8 ^{a}
$N_0P_1K_1$	1.7 ^{a}	3.3 ^{a}	5.6 ^{b}	7.3 ^{b}	9.9 ^{a}
$N_1P_0K_1$	2.6 ^{cb}	4.6 ^{bcd}	6.0 ^{bc}	9.2 ^{c}	10.3 ^{a}
$N_1P_1K_0$	2.1 ^{b}	4.1 ^{b}	6.6 ^{cd}	9.2 ^{c}	11.6 ^{b}
$N_1P_{0.25}K_{0.25}$	2.5 ^{cb}	5.2 ^{d}	6.8 ^{cd}	10.0 ^{c}	11.9 ^{cb}
$N_1P_{0.5}K_1$	2.7 ^{c}	4.9 ^{cd}	7.0 ^{d}	9.3 ^{c}	12.0 ^{bc}
$N_1P_1K_1$	2.4 ^{cb}	5.0 ^{cd}	6.8 ^{cd}	9.1 ^{c}	12.2 ^{bc}
$N_1P_1K_1$+Ca	2.8 ^{c}	4.4 ^{bc}	7.1 ^{d}	9.4 ^{c}	12.7 ^{c}

Means labeled with the same letter did not differ significantly at $P \leq 0.05$

based on yield quantity, have been revealed. The first two groups contain only a single treatment, i.e., the absolute control ($N_0P_0K_0$) and the fertilized with P and K ($N_0P_1K_1$), respectively. The difference of 1.4 Mg ha^{-1} is not only significant, but also indicates a yield forming action of both nutrients. The third group consists of treatments fertilized with N. The maximum WSY within this group was harvested in $N_1P_{0,25}K_{0,25}$. In this particular treatment, the highest WSY increase during the three-weekly period was also noted (47%). This treatment presents an optimal fertilizing structure but only for early harvested beets (Table 2).

The last sampling period, which took place at 175 DAS, showed a treatment-specific increase of WSY since 155 DAS. All studied treatments can be divided into three groups, presenting substantially different level of WSY increase:

- low (< 2 t ha^{-1}): $N_1P_0K_1$, $N_1P_{0,25}K_{0,25}$;
- moderate (2-3 t ha^{-1}): $N_0P_1K_1$, $N_1P_1K_0$, $N_1P_{0.5}K_1$;
- high (> 3 t ha^{-1}): $N_0P_0K_0$, $N_1P_1K_1$, $N_1P_1K_1$+Ca.

The first group (I) contains treatments, which significantly reduced sugar accumulation due to shortage of P. The second group (II) consists of treatments of different strategy of WSY development. The first treatment, with relatively low WSY, in fact, shows a high-sugar production potential of the soil under study. The second and the third one, in spite of high WSY, did not realize yielding potential of the crop. In the case of $N_1P_1K_0$, an imbalanced supply of K was the key reason for low sugar recovery (Barłóg et al., 2014). In the case of $N_1P_{0.5}K_1$ the yielding potential of the crop was restricted by shortage of P. The third group (III) consists of different treatments. The first one comprises only the absolute control. The found WSY increase, which took place in last three weeks of vegetation indirectly, confirms the high soil fertility level, provided ample water supply, as was in 2001. The same conclusion refers to fully balanced fertilizing treatments. The maximum WSY was a reason of high potential of beet to accumulate sugar and yield forming action of P, K, and Ca. The action of the last nutrient resulted in the WSY increase of 0.5 Mg ha^{-1} (Table 2).

Effect of the imbalanced nutrient supply was variable in consecutive years of study. The key difference relates to the WSY expression at harvest (175 DAS) in treatments of various degrees of balanced supply of N, P, K. In 2001, the highest WSY increase as compared to the absolute control was noted for $N_1P_{0.5}K_1$, $N_1P_1K_1$ and $N_1P_1K_1$+Ca. However, the most important was the progressive WSY increase in response to increasing P fertilizer rate. A very similar trend was observed in 2003, but the effect of P rate was not significant. The only effect of Ca, as a component of a fertilizer based on partially acidulated phosphoric rock, was pronounced. In 2002, the highest WSY was harvested in the $N_1P_{0.25}K_{0.25}$ treatment. Effect of balanced P fertilization was negative; yields on the N well-adjusted plots were much lower than in other years (Figure 1).

Table 3
Regression models of white sugar accumulation trends during vegetation season (n = 15)

Treatment	Equation	R^2 ($P \leq 0.001$)	DAS_t
$N_0P_0K_0$	WSY = -7.632 + 0.094 DAS	0.88	198.2
$N_0P_1K_1$	WSY = -7.661 + 0.099 DAS	0.87	188.9
$N_1P_0K_1$	WSY = -6.413 + 0.097 DAS	0.89	180.1
$N_1P_1K_0$	WSY = -8.704 + 0.115 DAS	0.89	170.7
$N_1P_{0.25}K_{0.25}$	WSY = -7.959 + 0.114 DAS	0.88	166.5
$N_1P_{0.5}K_1$	WSY = -7.656 + 0.111 DAS	0.83	168.4
$N_1P_1K_1$	WSY = -8.180 + 0.114 DAS	0.88	168.0
$N_1P_1K_1$+Ca	WSY = -8.706 + 0.120 DAS	0.80	164.8

WSY is white sugar yield in Mg ha^{-1}; DAS is number days after sowing; DAS_t is number of days after sugar beet sowing for WSY = 11.0 Mg ha^{-1}

Trend of sugar accumulation by beets throughout the season was progressive, following the linear regression model (Table 3). The reliability of the obtained equations, as confirmed by coefficients of determination (R^2), was higher compared to those for yield of beets (Barłóg et al., 2013). The tested variants have been evaluated by two criteria. The first refers to the directional coefficient of the linear equation “b”, which describes a daily rate of WSY increase. Based on it, the tested treatments can be arranged in the descending order:

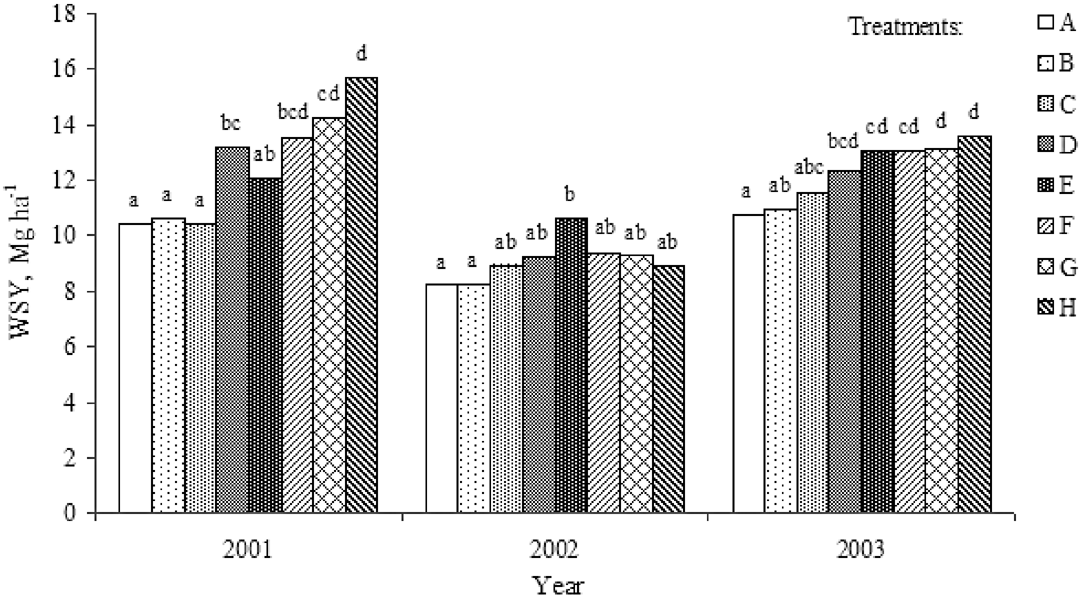

Fig. 1. Effect of balanced NPK fertilization on white sugar yield (WSY) at harvest (175 DAS) on the background of seasons. In Material and Methods section is detailed explanation of treatment symbols. Means labelled with the same letter did not differ significantly at $P \leq 0.05$, for each year separately

$N_1P_1K_1$+Ca = $N_1P_1K_0$ = $N_1P_1K_1$ > $N_1P_{0.25}K_{0.25}$ > $N_1P_{0.5}K_1$ = = $N_0P_1K_1$ > $N_1P_0K_1$ > $N_0P_0K_0$.

The second criterion was the number days after sowing (DAS_t) to obtain 11.0 Mg ha^{-1} of WSY. The DAS_t to reach the target yield was *ca* 198 for the absolute control and less than 165 for $N_1P_1K_1$+Ca treatment (Table 3). The presented order of treatments implicitly underlines two facts. The first one refers to distinct difference between bi-nutrient treatments and NPK ones. The second one stresses the importance of P in white sugar production, as corroborated by the 10th-day difference between $N_1P_0K_1$ and $N_1P_1K_0$ to reach the target yield.

The yield of recovery sugar is a function of interaction of numerous characteristics of processing beets, such as yield and others describing their technical quality (Buchholz et al., 1995). The study clearly showed that the key factor, determining WSY in consecutive triweekly periods, was yield of beets. Effect of SC was positive, but of secondary importance. Effects of standard molassigenic compounds (AmN, K, Na), as a rule, was both negative, and at the same time highly year-to-year variable (Table 4).

Table 4

White sugar yield (WSY) as a function of beet yield (BY) and its technical quality – *BETA* coefficients of multiple regression (n = 24)

Independent variable	Days after sowing (DAS)				
	92	113	134	155	175
BY	1.065***	0.807***	1.012***	1.066***	0.909***
SC	0.267***	0.478***	0.286***	0.374***	0.366***
AmN	-0.055	-0.058*	-0.041*	-0.003	-0.022*
K	-0.002	-0.020	-0.013	-0.018	-0.011
Na	-0.003	-0.010	-0.032	-0.112*	0.026*
R^2	0.995	0.996	0.998	0.993	0.999

*, **, *** significant level for $P \leq 0.05$; 0.01; 0.001, respectively

The step linear regression model has been applied to evaluate an importance of yield components for prediction of WSY in consecutive sampling dates (Table 5). Yield of white sugar, based on the value of a coefficient of determination, R^2, was the best described by BY. The highest effect of BY on WSY was noted at 92 and 134 DAS, when R^2, amounted to 0.96 and 0.92, respectively. In the first sampling date, conducted at 92 DAS, addition of SC raised the R^2, just by 0.03 (0.99). At 134 DAS, it was necessary to include into the equation other characteristics, such as SC and AmN, to reach the level of 0.99. In three of five triweekly sampling intervals both SC and AmN were yield components, significantly increasing the WSY predictability. Only at 155 DAS, Na showed superiority to AmN. It is important to underline that K was not a factor limiting WSY in any stage of its formation (Table 5).

Table 5

White sugar yield (WSY) as a function of beet yield (BY) and beet quality – results of the step linear regression (n=24)

Harvest date (DAS)	Equation	R^2 ($P \leq 0.001$)
92	WSY = 0.245 + 0.092 BY	0.96
	WSY = -1.841 + 0.01 BY + 0.1521 SC	0.99
113	WSY = -0.6 + 0.150 BY	0.83
	WSY = -4.901 + 0.133 BY + 0.333 SC – 0.197 AmN	0.99
134	WSY = 0.266 + 0.132 BY	0.92
	WSY = -6.253 + 0.137 BY + 0.416 SC – 0.195 AmN	0.99
155	WSY = 0.762 + 0.14 BY	0.81
	WSY = -9.073 + 0.165 BY + 0.515 SC – 0.939 Na	0.99
175	WSY = -0.361 + 0.166 BY	0.86
	WSY = -12.334 + 0.162 BY + 0.7 SC – 0.171 AmN	0.99

Explanation: WSY is white sugar yield, Mg ha^{-1}; BY is beet yield, Mg ha^{-1}; SC is sucrose concentration, %; AmN is α-amino-N concentration, mM kg^{-1}; Na is beet Na concentration, mM kg^{-1}.

Discussion

The dynamics of WSY was evaluated during the period extending since 92 DAS up to the end of crop vegetation, which took place at 175 DAS. The triweekly period of each consecutive plant sampling was sufficiently long to quantify WSY response to imbalanced fertilization with P and K. The WSY forming effect of applied fertilizers was year-to-year variable, as dependent on nutrients supply during each of the seasons. External conditions, created by weather course throughout consecutive seasons, were decisive for yield potential of sugar beet realization. The pattern of sugar production by beets in 2001 was completely different compared to those in 2002 and 2003. The first, based on distribution of precipitation, can be evaluated as optimal, while others as dry. This in accordance to Kenter et al. (2006), who stated that in the Central Europe weather course in summer months, i.e., July and August, is a decisive factor of development the WSY.

The key question remains, whether is possible to predict final WSY (at 175 DAS), based on its in-season assessed yield or on the beet yield (BY). The first prediction of WSY was conducted using respective data for the 92 DAS. It was significant ($R^2 = 0.49$; $P \leq 0.001$) as presented in the Figure 2. Slightly lower predictability was achieved, using BY at 92 DAS as the independent variable:

$$WSY_{175} = 7.709 + 0.166\ BY_{92};\ R^2 = 0.37;\ P \leq 0.01;\ n = 24$$

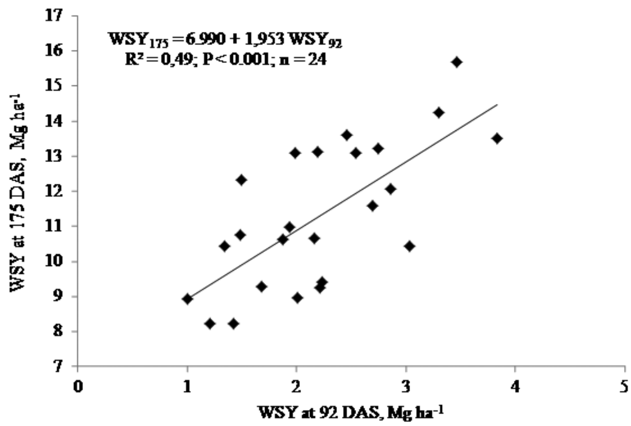

Fig. 2. Prediction of white sugar yield (WSY) at harvest (175 DAS) as a function of WSY at 92 DAS

The calculation procedure, conducted in other sampling dates, did show any advantage, over the first period. This conclusion is important for the practical reasons, because allows not only to predict the WSY but also to indicate a day of the fixed yield. In spite of lower R^2 values, yield of beets (BY) at 92 DAS is a useful and at the same time an ease tool for making a reliable WSY prediction.

The study implicitly showed that in 2001, WSY of beets fertilized with NPK increased in accordance to increasing rates of P, in spite of sufficiently high soil P fertility. This phenomenon has not been observed in 2002 and 2003. The maximum WSY, averaged over both years, was noted for $N_1P_{0.25}K_{0.25}$, i.e., for the treatment with the reduced amount of applied P and K fertilizers. Based on this finding one could choose a conclusion that maximum productivity of sugar beet can be exploited, based mostly on soil P and K resources. This statement, in the light of the obtained data, is wrong. Much lower WSY in 2002 and 2003 years compared to 2001 can be explained through analysis of yield forming functions of N, which efficiency depends on supply of other nutrients.

There is very difficult to divide, based on morphological characteristics, the whole growing season of sugar beet into certain periods (Bell et al., 1996). However, WSY forming action of key nutrients is slightly different in consecutive stages of the crop growth. In the earliest stages of sugar beet growth, the limiting factor is the rate of leave's growth. Interception of solar radiation by the sugar beet canopy is efficient provided its leaf area index (LAI) is of 3 (Andrieu et al., 1997). The required sum of temperatures to reach this target is of 900°C and N accumulation of 120 kg ha^{-1} (Werker and Jaggard, 1998; Malnou et al., 2006). Potassium has been recognized as the factor seriously limiting uptake of NO_3–N by plants, in turn disturbing their rate of growth and partitioning of assimilates between leaves and roots (Marschner et al., 1996; Winzer et al., 1996). It has been documented than inadequate supply of K significantly reduces both N accumulation and in consequence, aboveground biomass of leaves at the stage of 5–6th leaf (Grzebisz at al., 2005). Sugar beet in years with water shortage, i.e., in 2002 and 2003, responded considerably to unfavorable conditions, as confirmed by ca 30% loss of WSY at 92 DAS.

The mead-season of sugar beet growth covers the period of linear biomass growth, which for leaves extends from the first decade of July up to the end of the second (third) decade of August. This period is important for the development of the storage root as the physiological sink of sugar accumulation. The key questions remains, why water shortage limits the size of the sugar sink. It has been documented that sugar beet to keep the maximum rate of biomass growth takes up K with the rate of 10 and 9 kg ha^{-1} d^{-1} for 7 and 17 consecutive days, respectively (Grzebisz et al., 1998). It is well recognized, that any water shortage restricts the rate of immobile nutrients such as P and K movement from the soil towards the root (Jung and Classen, 1997). Consequently, the uptake rate of NO_3–N is reduced, in turn negatively affecting the rate of the above-ground biomass increase (Marschner et al., 1996). In 2001, the rate of roots biomass growth during the periods extending from 113 to 134 DAS was double compared to other years, with drought. In this particular year, content of K in the beet brei, in spite of a very high WSY, was much higher than in other two years (Barłóg et al., 2014). It means that not only K but also N supply to plants was reduced in years with drought, in turn decreasing the size of beet physiological sink for sugar.

The explanation of both nutrients' action requires inside into the morphological structure of the storage root. The sugar beet root tissue is composed of several concentric secondary cambia (rings), developing simultaneously during root growth. The single ring of the storage root is composed of the adjacent small-sized cells in the vascular zone and large-sized cells in the parenchyma zone. The size and development of the parenchyma zone depend on supply of N (Bell et al., 1996). This hypothesis is corroborated by distribution of α-amino N within the root. It is the highest in the upper part of the storage root, being responsible for the technological root in-season growth (Mahn et al., 2002). The adequate supplies of N depend, however, on P and K. Both nutrients must be readily available to the crop to keep it's vigorously growth over the key stages of yield formation (Cakmak, 2005; Kuchenbuch et al., 2006). Therefore, any shortage of K during the linear period of sugar beet growth, which coincides with the highest rate of storage root's growth, is critical to development of its sugar accumulation sink.

The above formulated hypothesis has been corroborated in the study by evaluation yield forming action of P. It has been documented that its uptake by sugar beet sharply increases in the late-season (Grzebisz et al., 1998). It has been also well recognized that P is responsible for many basic processes, such as energy production, photosynthesis, sucrose synthesis, etc. (Marschner, 1995). Therefore, beet plants correctly supplied with P are able to produce efficiently sucrose, subsequently increasing its storage in the root. However, as shown in Table 5, the key factor responsible for WSY is the BY, in turn representing a physiological sucrose sink. Plants of limiting capacity for sucrose accumulation, due to restricted root's size, are not able to exploit fully WSY in the late-season. Consequently, in dry years the only compensation rout is via increased SC in a root, but its capacity is limited, as revealed in 2003. The yield forming importance of P has been fully corroborated in the conducted study. The WSY increase in the last triweekly period of growth was in the range of 30-40% in treatments well balanced, i.e., $N_1P_{0.5}K_1$, $N_1P_1K_1$, $N_1P_1K_1$+Ca. Plants fertilized with reduced supply of P to 25% of the recommended P rate increased WSY by less than 20%. The highest increase was noted for $N_1P_1K_1$+Ca treatments, where P was applied in the form of partially acidulated phosphoric rock. This type of fertilizer is reach in Ca. This nutrient is important due to its multifunctional impact on plant metabolism (White and Broadley, 2003). So far, in sugar beet, its yield forming function is weakly recognized. The proposed hypothesis is in accordance to other experimental data. As shown by Nikolova (1999) the highest yield of sugar was harvested in plots with recommended full rates of P and K.

Conclusions

The study implicitly showed that weather course during the growing season was a factor decisive for the response of WSY to imbalanced fertilization. In the season with favorable growing conditions WSY depended on supply of P. The yield forming effect of this nutrient is the most conspicuous in the late-season. In the last period of growth plants correctly supplied with P could increase of WSY by 30-40%. Plant fertilized with the decreased amount of fertilizer P showed a much lower yield increase in the respective period. The average WSY increase in response to optimal P application was 1.9 Mg ha^{-1}, whereas of K only 0.4 Mg ha^{-1}. Even higher yield increase was noted, when P applied in the form of partially acidulated phosphoric rock (2.4 Mg ha^{-1}). The direct reason of the low-yield increase in the late-season was the reduced size of the physiological sink of a root to accumulate sugar. The key reason was drought, which limited the rate of the storage root growth in both the early- and the mead-season (113-134 DAS). Consequently, at 92 DAS, the temporary WSY was by 30% lower in years with drought compared to the year with ample water supply. In years with water shortage, the increase of SC in the storage root is the only possible compensation route for WSY increase. The first significantly reliable prediction of final WSY, based on in-season yield of beets and/or yield of white sugar can be conducted at 92 DAS.

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