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SUGAR BEET RESPONSE TO BALANCED NITROGEN FERTILIZATION WITH PHOSPHORUS AND POTASSIUM

PART I. DYNAMICS OF BEET YIELD DEVELOPMENT

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Abstract

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The objective of the conducted study was to determine the effect of various levels of P, K under the background of constant N rate on dynamics of sugar beet root yield. The field trial, arranged as a 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 N, P, K application and Ca means that phosphorus applied as partially acidulated phosphoric rock (PAPR). The in-season yield sampling was conducted at 92, 113, 134, 155 and 175th day after sowing. The highest degree of yield potential realization revealed in the year with favourable weather conditions. The highest yield was harvested on the plot fertilized with $N_1P_1K_1$+Ca. In years with extended drought, sugar beet achieved the maximum yield in the treatment $N_1P_{0.25}K_{0.25}$. Phosphorus revealed as the key yield forming factors, i.e., limiting N unit productivity. The maximum productivity of N occurred in treatments with full P rate, especially when P fertilizer was applied as the PAPR. However, phosphorus yield forming action depended on weather conditions in the mead-season and P fertilizer rate. The first factor, affecting N and K supply to sugar beet during the mead-season, was responsible for the size of the beetroot, considered as the sugar storage. Any drought, negatively impacting its size, in turn decreases P yield forming action, which appears in the late-season. The maximal exploitation of sugar beet yielding potential is, therefore, possible provided water is not a factor limiting sugar beet growth in the mead-season and P in late-season. Nevertheless, in farming practice, the lack of favourable growth conditions should not be a reason for development a sugar beet fertilizing strategy, based on reduced P and K rates.

*Key words***:** balanced fertilization, beet yield, growth dynamics, partial factor productivity, agronomic efficiency

Introduction

Yield potential of sugar beet (*Beta vulgaris* L.) depends upon several factors. Intensity of solar radiation intercepted by the canopy, temperatures at critical stages of growth, and distribution of precipitation are the main limiting growth factors. Kenter et al. (2006), based on climatic factors, has calculated yield potential of sugar beet in Europe at the level ranged from 110 to 150 Mg ha^{-1}. The maximum attainable yield of varieties currently cultivated in Poland is of 80 Mg ha^{-1}. In contrast, yields harvested by farmers share only 50-60% of the current yield potential of this crop (Supit at al., 2010). There are some principal reasons behind this state such as acid soils, low content of available soil P, K and Mg and unbalanced N, P, K fertilization (Grzebisz et al., 2002; Barłóg et al. 2010; Grzebisz and Diatta, 2012).

It is well documented that N is the nutrient limiting the most sugar beet productivity (Hergert, 2010). The application of too little N results in reduced root yield. Contrary, high amount of applied N is the cause of imbalanced partitioning of assimilates among leaves and storage root, and lead to decrease of root sucrose concentration. Its oversupply, increases also concentrations of impurities, such as α-amino-N, K, Na, in turn decreasing storage root quality (Hoffmann, 2005; Malnou et al., 2008). Therefore, the most important purpose of sugar beet growers is to increase nitrogen use efficiency.

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Any efforts towards fulfilment this objective requires to take into account both N and other nutrients, especially of P and K (Nikolova, 1999; Draycott and Christenson, 2003; Römer et al., 2004; Grzebisz et al., 2012).

Phosphorus functions in plants are numerous, comprising energy transfer, photosynthesis, transformation of sugars, transfer of genetic information and nutrient movement within the plant (Marschner, 1995). Potassium is involved in enzyme activation, charge balance and osmoregulation in plants (Cakmak, 2005). In sugar beet, K plays a significant role in biosynthesis and transfer of sucrose to storage roots (Winzer et al., 1996). It is assumed that P and K fertilizing increases both, yield and beet quality. However, a response of sugar beet to both nutrients, applied as fertilizers, depends on interaction of numerous factors. Among the most important are weather conditions during the vegetation, soil type and initial content of available forms of these nutrients (Milford et al., 2000; Römer et al., 2004; Barłóg et al., 2010).

Nutrient management in Central Europe is mainly N oriented, resulting in high-year-to-year variability of harvested yields. The low consumption of key nutrients, P and K, due to their insufficient supply, creates unfavourable growth conditions for crops. At the beginning of the XXI century, the consumption ratio of principal nutrient's N:P_2O_5:K_2O in Poland was as follows: 1:0.35:0.41, while it should be at the level of 1:0.5:1.0, at least (Grzebisz and Diatta, 2012). Nowadays, balanced crop nutrition with N, regarding its uptake, accumulation in soil, and protection of environment is one of the key targets in sustainable concept of agricultural production in the 21st century (Tzilivakis et al., 2005). To break this negative tendency is to balance the applied N fertilizer using adequate rates of P and K. Therefore, the most important challenge for sugar beet producers is to fix a right rate of N at the background of P and K supply during the growing season or vice versa.

It has been formulated a hypothesis that sugar beet yield depends much more of currently applied P and K fertilizers that on the initial soil fertility. The main purpose of the conducted study was to evaluate the effect of different N:P_2O_5:K_2O ratios on patterns of sugar beet yield growth during the vegetative season.

Material 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 soil under the experiment is, according to FAO/WRB, classified as Haplic Luvisols. It originated from loamy sand underlined by loam. According to the Polish agronomic system, it is classified as the IVa class, i.e., good rye complex and the agronomical category - light soil. Soil samples (0–0.3 m) were taken in autumn before application of fertilizers. After air-drying, soil properties were determined according to the standard method: particle size distribution by Casagrande's aerometric method in Prószyński modification; pH in 1 M KCl (Van Lierop, 1990); available form of P and K by DL (Egnér-Riehm) method (Egnér et al., 1960). The topsoil was characterized by an optimal soil reaction (pH); higher (2001–2002) and mean (2003) level of present form of P, and mean (2001–2002) and low (2003) level of K (Table 1).

A completely randomized experimental design was employed with four replications and area of 54 m² 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

Table 1
Physical and chemical properties of soil under study (0.0–0.3 m)

Year	Soil particles ¹⁾, %			pH ²⁾	Soil available form ³⁾	
	Sand 2–0.05 mm	Silt 0.05–0.002	Clay <0.002 mm		P mg kg^{-1}	K mg kg^{-1}
2001	78	16	6	6.0	81	113
2002	84	10	6	5.9	85	118
2003	75	21	4	5.5	60	77

Methods: ¹⁾ Casagrande's aerometric method; ²⁾ 1 M KCl, 1:2.5 m/v ratio; ³⁾ DL-method 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 and 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 super phosphate (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 (Kassandra variety) was sown each year on April 15th. Plants were sampled at 92, 113, 134, 155 and 175th day after sowing (DAS). In all dates, plants were hand-harvested from an area of 3.6 m^2. At the stage of technological maturity (175 DAS), plants were harvested from an area of 18 m^2. At each date plant samples were partitioning into sub samples of leaves (= young and mature blades + young and mature petioles + crown) and taproots (= beet).

The long-term (1960-2001) average of annual precipitation in the area of research is about 600 mm. During the study, yearly precipitation varied from 314 mm (2003) to 637 mm (2002) and average temperature from 8.5°C (2003) to 8.9°C (2002). In the successive years of study, total precipitation during vegetation season (IV – X) amounted to 174, 121 and 85 mm, for 2001, 2002, and 2003, respectively.

The efficiency of N, P and K fertilization was calculated on the basis of the following parameters (Novoa and Loomis, 1981):

$$PFP = BY / R \qquad 1)$$

$$NAE = (BY - BY_0) / R \,, \qquad 2)$$

where, PFP is partially factor productivity of fertilizer nutrient (kg kg^{-1}), NAE is net agronomic efficiency (kg kg^{-1}), BY is beet yield at 175th day after sowing (kg ha^{-1}), BY_0 is beet yield on treatment without N, P or K, at 175th day after sowing (kg ha^{-1}), R is N, P_2O_5 or K_2O rate (kg 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. Linear regression was performed in order to find out relationships between beet yield and number of days after sowing (DAS). Data analysis was performed using the statistical package STATISTICA 9.

Results

Yields of sugar beets, measured at consecutive dates since the 92 DAS, showed significant dependence on interaction of year and fertilizing treatments (Table 2). The first factor can be considered as the major one. Interaction of both factors reveled as a different level of yielding expression of studied treatments. Hence, effect of particular treatments in each of consecutive dates of sampling, has been assessed, based on data averaged over years. Data for the 175 DAS, i.e., final harvest, has been described separately, in details.

On the average, the highest beet yield, irrespective on sampling date, was in 2001 (Table 3). The significant differences compared to other years, i.e., 2002 and 2003 were found since the first sampling date, i.e., at 92 DAS. This trend was almost constant up to 155 DAS. The most interesting problem refers to beet yield ingrowths following the maximum. In 2001, it was found a declining trend. In both dry years, plant response was different. In 2002, beet yield increase stagnated at the level of *ca* 9.0 Mg ha^{-1} for each 20th-day period. In 2003, it was progressive, revealing the occurrence of compensation mechanism, indirectly related to applied nutrients (Table 3).

Effect of fertilizing treatments on beet yield was at harvest year specific (Figure 1). On average, plants grown on the absolute control plot ($N_0P_0K_0$) yielded the lowest, but at the same level, as those fertilized without N ($N_0P_1K_1$) or without P ($N_1P_0K_1$). This is the first indicator that P was the most limiting yield forming nutrient. This conclusion was enforced by data resulting from analysis of NPK treatments (Table 3). Yield of sugar beet in-growth in the late-season showed high differences, related to P rates. The beet yield increase between 155 and 175 DAS, due to different levels of P application, was 16.5%, 22.4% and 26.2% for the $N_1P_{0.25}K_{0.25}$, $N_1P_{0.5}K_1$ and $N_1P_1K_1$, respectively. However, the highest yield

Table 2
Statistical evaluation of factors affecting beet yield (BY); F values of two-way ANOVA

Factors	Days after sowing (DAS)				
	92	113	134	155	175
Years (Y)	85.0^{***}	8.3^{***}	96.3^{***}	110.0^{***}	147.3^{***}
Fertilizing treatments (F)	25.0^{***}	24.5^{***}	22.6^{***}	25.5^{***}	20.3^{***}
Interaction Y x F	5.6^{***}	4.6^{***}	7.9^{***}	5.9^{***}	3.6^{***}

*, **, *** significant level for P ≤0.05; 0.01; 0.001, respectively

increase of 28.1% was noted for the treatment $N_1P_1K_1$+Ca. The predominance of the latter treatment was observed for the whole period since the 92 DAS. It can be, therefore concluded that the degree of sugar beet yielding potential expression depends on the mead-season rate of growth, modified by supply of nutrients. This crop can compensate largely its final rate of growth. The second conclusion has been formulated, based on yield in-growth, which took place between 155 and 175 DAS on the control plot, which amounted to 53.6% (Table 3).

Yield of storage root showed a progressive increase up to the end of vegetation. Therefore, dynamics of storage root yield during the growing season is the best described by the linear regression model (Table 4). The impact of studied treatments on the yield trends has been evaluated by two coefficients, i.e., determination (R^2) and directional (d). The second one describes the daily rate of the beet yield increase (Mg ha^{-1} day^{-1}). With respect to the first indicator, it was found, a sufficiently high probability of final yield prediction ($P \leq 0.001$). In spite of this, the highest R^2 was the attribute of $N_1P_{0.25}K_{0.25}$ and $N_1P_0K_1$ treatments. This finding collaborates with the conclusion about the limiting effect of P on final yield of beets. The predominant yield forming function of P was also underlined by the directional coefficient. The highest daily root yield increase, i.e., above 0.6 Mg ha^{-1}, was related to $N_1P_1K_1$+Ca, $N_1P_1K_0$, and $N_1P_1K_1$, treatments (Table 4).

The second criterion used to evaluate the impact of studied treatments on final beet yield was a number of days after sowing (DAS_t) required to reach the fixed yield of 70 Mg ha^{-1}. The analysis of equations included in Table 4 showed that the level of N balancing by other nutrients, including also Ca, minimized the values of DAS_t. The final beet yield (BY at 175 DAS) can be, therefore, predicted with higher accuracy based

Table 3

Effect of fertilizing treatments on beet yield (BY) in depending on the years, treatments and harvest date (Mg ha^{-1})

Factor	Days after sowing (DAS)				
	92	113	134	155	175
Year					
2001	28.6^{b}	35.1^{b}	55.1^{b}	68.5^{b}	81.0^{c}
2002	19.5^{a}	31.5^{a}	41.2^{a}	50.0^{a}	59.5^{a}
2003	18.4^{a}	31.6^{a}	40.4^{a}	51.5^{a}	70.2^{b}
Treatment					
$N_0P_0K_0$	13.2^{a}	23.9^{a}	32.3^{a}	39.4^{a}	60.5^{a}
$N_0P_1K_1$	16.6^{ab}	24.5^{a}	40.9^{b}	49.3^{b}	64.0^{a}
$N_1P_0K_1$	25.0^{cd}	35.6^{bc}	44.6^{bc}	59.5^{c}	64.2^{a}
$N_1P_1K_0$	20.8^{bc}	31.5^{b}	47.8^{cd}	59.8^{c}	70.7^{b}
$N_1P_{0.25}K_{0.25}$	23.7^{cd}	37.9^{c}	47.5^{cd}	63.0^{c}	73.4^{bc}
$N_1P_{0.5}K_1$	26.4^{d}	36.4^{bc}	50.3^{cd}	60.8^{c}	74.4^{bc}
$N_1P_1K_1$	24.5^{cd}	38.5^{c}	47.6^{cd}	60.7^{c}	76.6^{bc}
$N_1P_1K_1$+Ca	27.3^{d}	33.4^{bc}	53.5^{d}	60.8^{c}	77.9^{c}

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

Table 4

Regression models of the beet yield (BY) growth during vegetation season (n=15)

Treatment	Equation	R^2 ($P\leq0.001$)	DAS_t
$N_0P_0K_0$	BY = -36.8 + 0.528 DAS	0.86	202.2
$N_0P_1K_1$	BY = -37.9 + 0.575 DAS	0.81	187.6
$N_1P_0K_1$	BY = -20.1 + 0.492 DAS	0.87	183.0
$N_1P_1K_0$	BY = - 36.2 + 0.616 DAS	0.83	172.6
$N_1P_{0.25}K_{0.25}$	BY = -31.0 + 0.599 DAS	0.89	168.6
$N_1P_{0.5}K_1$	BY = -27.9 + 0.579 DAS	0.75	168.9
$N_1P_1K_1$	BY = -31.7 + 0.608 DAS	0.83	167.4
$N_1P_1K_1$+Ca	BY = -32.0 + 0.618 DAS	0.74	165.2

BY is beet yield in Mg ha^{-1}; DAS is number days after sowing; DAS_t is number of days after sugar beet sowing for BY=70.0 Mg ha^{-1}

on DAS_t than on directional coefficient (dc). These dependencies are presented below:

$$BY_{175} = 5.172 + 112.7\ d\ c$$
$$R^2 = 0.61;\ P \leq 0.05;\ n = 8 \qquad 3)$$

$$BY_{175} = 155.1 - 0.480\ DAS_t$$
$$R^2 = 0.91;\quad P \leq 0.001;\ n = 8 \qquad 4)$$

Hence, both the final beet yield and the time required to harvest the maximum beet yield significantly related to management of nutrients. The fertilizing strategy oriented on greatest balancing of N allows to reach a very high yield and to harvest it much earlier than in the case of reduced rates of P. This nutrient can be, therefore considered as the most limiting for exploiting yield potential of sugar beet, because its yield forming functions prevails up to the end of this crop vegetation.

Two indices of nutrient agronomic efficiency have been applied to evaluate productivity of N, P and K. The partial factor productivity of applied N fertilizer (PFP_N) was, except, the $N_1P_0K_1$ treatment in the range of 520–560 kg beet's kg^{-1} N. Its value of 463.5 kg beet's kg^{-1} N, as calculated for the $N_1P_0K_1$ treatment, is a direct answer on the limiting effect of P (Table 5). The yield forming importance of P was corroborated by analysing both the net agronomic efficiency of N (NAE_N) and efficiency factors related to applied P fertilizer (PFP_P and NAE_P). The latter ones implicitly showed that the higher P rate the lower its unit productivity. In addition, plant well supplied with P, as found for $N_1P_1K_1$ and $N_1P_1K_1$ + Ca treatments, caused a further increase of a N unit productivity by *ca* 20 and 30 kg beet's kg^{-1} N, respectively. Unit productivity of applied K fertilizer was negative in the treatment without P ($N_1P_0K_1$). In other treatments, its unit productivity was low, indirectly indicating on adequate supply of K.

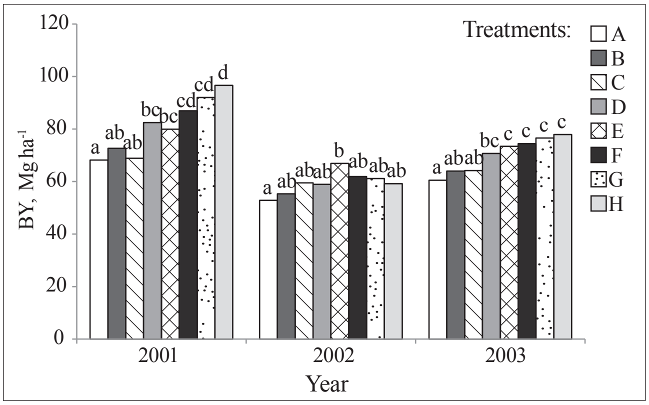

Fig. 1. Effect of balanced NPK fertilization on beet yield (BY) at harvest (175 DAS) on the background of seasons. In Material and Methods section is the detailed explanation of treatment symbols. Means labelled with the same letter did not differ significantly at $P \leq 0.05$, for each year separately

Discussion

In the temperate regions of the World, including Poland, total amount and distribution of precipitation is the key factor limiting yield formation by sugar beet (Frecleton et al., 1999; Kenter et al., 2006). During study, effect of weather was very pronounced since the beginning of crop growth. The extended drought, which occurred in 2002 and 2003, overlapped the most critical stages of yield formation. As a result, beet yields at the 92 DAS were by $^1/_3$ and at 134 DAS ½ lower compared to 2001. At the first stage, both leaves and storage root reaches the highest absolute rate of dry matter accumulation (Grzebisz et al., 2012). Under ample water supply, the high progress of beet yield in-growth extended up to August. In 2001, the beet yield increase was double compared to those noted in years with drought. This result is simply explained by the amount of precipitation in this critical month. In 2001, it was 77 mm in 2001, while only 39 mm in 2002 and 30 mm in 2003. This crop for adequate growth requires 90 mm of water (FAO, 2012). In spite of bad weather conditions, final

Table 5
Effect of balanced NPK fertilization on partial factor productivity (PFP) and net agronomic efficiency (NAE) of applied nutrients, kg kg^{-1}

Treatment	Nitrogen (N)		Phosphorus (P_2O_5)		Potassium (K_2O)	
	PFP_N	NAE_N	PFP_P	NAE_P	PFP_K	NAE_K
$N_0P_1K_1$	--	--	977.7	-2.8	308.1	-32.2
$N_1P_0K_1$	463.5	1.3	--	--	309.0	-31.4
$N_1P_1K_0$	510.5	48.4	1080.0	99.6	--	--
$N_1P_{0.25}K_{0.25}$	530.4	68.2	4488.2	566.5	1414.5	53.0
$N_1P_{0.5}K_1$	537.6	75.4	2274.3	313.4	358.4	18.0
$N_1P_1K_1$	553.2	91.1	1170.3	189.9	368.8	28.5
$N_1P_1K_1$+Ca	562.8	100.6	1190.5	210.1	375.2	34.5

beet yields, were in 2002 only by 27% and in 2003 by 13% lower compared to the average in 2001 (Table 3).

In the light of above presented facts, the key problem concerns yield forming functions of P and K. Effect of tested fertilizing treatments were variable, depending on the weather course. This is in agreement with study other studies (Milford et al., 2000; Macák et al., 2007). However, in spite of year-to-year variability, the highest yields, averaged over years, were harvested on treatments with fully balanced N. In 2001, beet yield increased along the increasing degree of N balancing. The highest yield produced crop grown in the treatment $N_1P_1K_1$+Ca (Figure 1). The harvested yield of 97 Mg ha^{-1} beets was by 30 Mg ha^{-1} higher than the potential yield for the cultivated variety (COBORU, 2004). In 2001, the combination of elevated soil K fertility, P recommended rate and high precipitation in August, with respect to sugar beet plants water needs, created favourable conditions for growth and resulted in full expression in storage root yield. Our results corroborate earlier studies about the positive response of sugar beet to PK fertilizers to exploit its yielding potential (Wiebel and Orlovius, 1996; Nikolova, 1999; Barłóg et al., 2010; Grzebisz et al., 2012).

In years with drought, beet yields were significantly lower. There were not found any significant differences between treatments with recommended and decreased rates of PK fertilizers. Under these conditions, the reduced amount of PK ($N_1P_{0.25}K_{0.25}$) was sufficient to harvest the highest yield. The coefficient of variability for this particular treatment was the lowest (10%). The lack of yield response to increasing K fertilizer rates is probably related to the very high supply of soil K. Accordingly, to Herlihy (1992) potassium application to soil with high level of available K can result in storage root decrease. This case was noted in 2002. Therefore, when the pre-sowing K application did not increase yields over the K control, the yield increase is not limited by K fertilization.

The development of beet yield in response to balanced application of N, P; K is weakly recognized during the growing season. For this purpose, the sigmoid-like regression models are recommended (Vandendriessche, 2000). This model allows indicating phases of different rate of the root biomass increase. In our study, fresh biomass of beets was measured first at the 92 DAS. At this particular stage sugar, beet reaches the highest rate of absolute growth of storage root (Grzebisz et al., 2012). The linear regression model fitted the best each set of data covering the period from 92 DAS up to 175 DAS. This model simply informs that yield of roots increased with a constant rate during the vegetation. The final yield of roots was, however, much more related to the number of days to reach the fixed yield of 70 Mg ha^{-1} (DAS_t) than to its daily rate (equations No. 4 and 3 respectively). The harvested yield at final harvest (BY_{175}) can be, therefore predicted on its biomass at 92 DAS (BY_{92}). This dependency is shown by the equation:

$$BY_{175} = 45.245 + 1.1257\ BY_{92};\quad R^2 = 0.52;\ P \le 0.001;\ n = 24 \qquad 5)$$

This conclusion corroborates some other studies, indicating the importance of optimal nutritional status of sugar beet during early stages of growth for final yield (Milford et al., 1985; Malnou et al., 2006).

The yield forming functions of all three nutrients requires a special time-dependent analysis. A temporary yield of beet, as determined at 92 DAS, showed much higher dependence on K and N than on P supply. The first two nutrients are decisive for the rate of leave's area growth, in turn responsible for assimilation of carbohydrates. It is worth a mention that number of consecutive leaves is a function of temperature, but their size depends on supply of N (Andrieu et al., 1997; Werker and Jaggard, 1998; Malnou et al., 2006). According to Grzebisz et al. (2012), the highest growth rate for beet leaves and taproots, growth occurs in the mead-season of sugar beet development and then progressively decline. This growth parameter responds significantly during the season to the variability of N concentration in both sugar beet organs. An adequate N uptake by growing plants requires a balanced supply of K (Giroux and Tran, 1989). The study implicitly showed that P was the key nutrient, limiting final yield of beets. However, its yield forming action was less effective due to growth disturbance, which occurred in mead-season during yield formation, which depends on supply of N and K. Potassium and nitrogen are responsible for development, the size of the sucrose sink, as defined by the number of rings and cells in the storage roots (Bell at al., 1996). Therefore, the mead-season conditions for root growth can be considered as a prerequisite for the P requirements in the late-season. The dominant yield forming function of P appeared in last period of sugar beet growth. The tested treatments, in accordance to the beet yield increase in the period between 155 and 175 DAS, represent one of three groups:

i) very high (> 50%): $N_0P_0K_0$;
ii) high (30–40%): all NPK, $N_0P_1K_1$;
iii) low (<20%): $N_1P_0K_1$ i $N_1P_1K_0$ oraz $N_1P_{0.25}K_{0.25}$.

The first group, comprising only the absolute control plot, indicates the balanced supply of nutrients, but leading to the deep exploitation of soil nutrient reserves. The degree of their use depends on weather conditions during the vegetation, including also the late-season. The harvested yields are, in general, low as compared to the second group, which consist of N balanced treatments. As a result, their yielding potential is high, but can be exploited only under ample supply of water, N and K, during the mead-season. The third group is composed of treatments, lacking one of the key nutrients. In the studied case, it was P. The decreased level of PK under ample supply of water could become a yield-limiting factor. Therefore, the reduced strategy of PK application should not be recommended in farming practice.

Conclusion

The exploitation of yielding potential of sugar beets depended, as shown in the study, on interaction of two key factors, i.e., water and nutrients supply. The highest beet yield can be obtained under conditions of favourable weather and adequate supply of fertilizers. Under these conditions, yield-forming functions of nutrients revealed at different stages of sugar beet growth. There can be distinguished three main periods of beet yield formation. Nitrogen and potassium dominate in early and in the mead-season, building up the physiological basis for the final yield of beets. Both nutrients are responsible for the degree of sugar beet rate of storage root growth in the mead-season, as the prerequisite of the final yield. Under stress conditions as impaired by low supply of water, the basis for final yield is reduced. Therefore, the P and K rate of 25% of the recommended rate is sufficient to cover the plant requirements for relatively moderate yield of beets. Under favourable growth conditions, the basis for elevated yield is fully developed, as a prerequisite of increased requirements of a crop for P. In the late-season, the crop yield potential fulfilling depends, therefore, on P supply. This nutrient is responsible for N unit productivity, provided an adequate rate of P. In addition, P applied in the form of partially acidulated phosphoric rock, indirectly underlines yield-forming functions of Ca.

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