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EFFECT OF DIFFERENTIATED FERTILIZING SYSTEMS ON NITROGEN ACCUMULATION PATTERNS DURING THE GROWING SEASON – SUGAR BEET AS AN EXAMPLE

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Abstract

The rate of nitrogen uptake by sugar beet canopy during the growing season is a driving factor in both dry matter production and its distribution between leaves and the storage root. It has been hypothesized that nitrogen accumulation in both parts of the beet is significantly affected by the regime of P and K supply to plants. This assumption has been verified with the data obtained from a field static experiment, conducted in 2001-2003, with eight fertilizing variants: without nitrogen (absolute control, PK), without one of the main nutrients (KN, PN), with a reduced amount of phosphorus and potassium (N + 25% PK, N + 50% PK) and with the recommended amounts of basic nutrients (NPK, $NP^{*}K$, P^{*} – P in the form of PAPR). Amounts of in-season accumulated nitrogen in sugar beet parts were measured on eight consecutive sampling dates, in two- to three-week intervals. The general pattern of N accumulation in leaves is best described by a quadratic equation, but follows a linear function in storage roots. The maximum rate of nitrogen accumulation depended on years and fertilizing variants. Limited supply of nutrients to beet plants, caused by the course of the weather or the applied fertilizers (less than 50% of the recommended N rate and without K), was the main reason for a lower rate of nitrogen accumulation in storage roots in the first part of the growing season. The course of absolute and relative nitrogen uptake rates shows that in the second part of the season the sugar beet could compensate the uptake of N from its soil resources. However, the effect of compensatory N uptake on yield of storage roots was inconsistent. When water and nutrients were in ample supply, e.g. in 2001, the additionally absorbed nitrogen could be used as an indicator of the yield potential of sugar beet. Under other growth conditions, it is used

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mainly for restoration of leaf growth, with a different effect on the final yield of storage roots. The quadratic trend of N accumulation in beet canopy during the growing season reflects the crop's N saturation status, a prerequisite of high yields of storage roots, as in 2001. The linear model, manifesting itself in years with pronounced drought, represents a sub-optimal status of N management in sugar beet canopy, resulting in much lower yields.

Key words: sugar beet, fertilizing variants, N accumulation patterns.

WPŁYW ZRÓŻNICOWANYCH SYSTEMÓW NAWOŻENIA NA WZORCE AKUMULACJI AZOTU W OKRESIE WEGETACJI – NA PRZYKŁADZIE BURAKA CUKROWEGO

Abstrakt

Szybkość pobierania azotu przez plantację buraki cukrowe w okresie wegetacji jest czynnikiem decydującym zarówno dla produkcji, jak i rozdziału suchej masy między liście i korzeń spichrzowy. W związku z tym postawiono tezę, że akumulacja azotu w obu częściach rośliny istotnie zależy od reżimu zaopatrzenia rośliny w P i K. Postawioną tezę zweryfikowano w doświadczeniu polowym statycznym, prowadzonym w latach 2001-2003, w którym zastosowano 8 wariantów nawozowych: bez azotu (kontrola absolutna, PK), bez jednego głównego makroskładnika (NK, NP), ze zredukowana dawką P i K (N + 25% PK; N + 50% PK) oraz z zalecaną dawką składników (NPK, NP*K, P* – P w nawozie fosforowym, tzw. wzbogaconym). Ilość azotu akumulowanego przez buraki w okresie wegetacji mierzono w 8 kolejnych terminach w cyklach dwu- do trzytygodniowych. Ogólny model akumulacji azotu w liściach buraków najlepiej opisuje równanie kwadratowe, a w korzeniach – liniowy. Maksymalna szybkość akumulacji azotu zależała istotnie od lat i wariantu nawozowego. Ograniczone zaopatrzenie roślin w skladniki pokarmowe, wynikające zarówno z przebiegu pogody w sezonie wegetacyjnym, jak i wariantu nawozowego (dawka P i K poniżej 50% dawki zalecanej), było główną przyczyną mniejszej szybkości akumulacji azotu przez korzenie buraków w pierwszym okresie wegetacji. Przebieg krzywych bezwzględnej i względnej akumulacji azotu w okresie wegetacji wskazuje na zdolność buraka cukrowego do kompensacji pobierania tego składnika z jego rezerw w glebie w drugiej części okresu wegetacji. Efekty plonotwórcze kompensacyjnego pobierania azotu nie są jednoznaczne. W warunkach optymalnego zaopatrzenia roślin w wodę i skladniki pokarmowe, t.j. w 2001 r, dodatkowo pobrany azot jest wskaźnikiem realizacji potencjału plonotwórczego buraków. W innych warunkach wegetacji dodatkowo pobrany azot zostaje zużyty na odtworzenie liści, z różnym skutkiem dla końcowego plonu korzeni. Model kwadratowy akumulacji azotu w okresie wegetacji odzwierciedla stan wysycenia roślin azotem, warunkując duży plon korzeni, jak w 2001 roku. Model liniowy, ujawniający się w latach z wyraźnie zaznaczoną suszą, przedstawia suboptymalny stan gospodarki azotem na plantacji buraków, prowadząc jednakże do zmniejszenia plonu korzeni.

Słowa kluczowe: burak cukrowy, warianty nawożenia, dynamika akumulacji azotu.

INTRODUCTION

The main aim of farmers producing sugar crops may seem self-contradictory because of the reciprocal relationships occurring between a high storage roots yield and its technological quality. Adequate nitrogen management is needed in order to obtain both goals.

On the one hand, high yields of storage roots are significantly related to the amount of nitrogen taken up by plants during the growing season. On the other hand, excess nitrogen in beet plant at harvest results in a high content of soluble nitrogen compounds, which deteriorate the quality of storage roots (BURBA 1996, HOFFMANN 2005).

God nitrogen management in sugar beet farming, a driving factor in sugar production, is difficult due to many factors. Supply of nitrogen to plants throughout the growing season depends on both soil N resources and externally applied nitrogen fertilizers. In addition, the distribution of assimilates between the storage root and leaves is strongly influenced by the soil nitrogen dynamics. The size of this N pool significantly depends on the weather course during the season. The weather is the primary factor shaping the soil N rate mineralization, and it is highly unpredictable. Consequently, the relationship between N accumulation in beets and applied rates of fertilizer nitrogen is typically a weak one (MALNOU et al. 2008, WERKER et al. 1999).

The yield potential of sugar beet in most areas of Europe can be considerably impaired due to the shortage of water during both early and later stages of the crop's growth. It is strongly affected by the weather variability, especially in summer months (KENTER et al. 2006). However, the impact of the weather can be modified by a soil nutrient regime, which can at least partly control water shortages (GRZEBISZ et al. 2002). The degree to which production resources can be substituted depends on the nitrogen management, as pointed out by FRECKLETON et al. (1999). Therefore, the main problem for achieving efficient N management in sugar beet is to understand the degree of its impact on the dynamics of leaf and storage root growth throughout a growing season.

The objective of this study was to determine patterns of N accumulation in sugar beet parts, using the growth analysis procedure. In other words, we analyzed to what extends a fertilizing regime affects the dynamics of nitrogen accumulation during the course of a growing season.

MATERIAL AND METHODS

The study was based on sets of data obtained from a static field experiment, which was carried out on a private farm at Wieszczyczyn (52°02'N17°05'E) during three consecutive growing seasons 2001, 2002, 2003. The soil originating from sandy loam underlined by loam is classified according to the Polish system as class IV a, good rye complex, and in the agronomic categories as light soil. The field trial, arranged in a one-factor design replicated four times, consisted of eight treatments:

1. Control – absolute control, i.e. no applied fertilizers (acronym Control);
2. PK – only phosphorus and potassium (VPK, Variant PK);
3. NK – only nitrogen and potassium (VNK);

4. NP – only nitrogen and phosphorus (VNP);
5. NPK – basic set of nutrients, but P, K rates limited to 25% of adjusted quantity (V25);
6. NPK – basic set of nutrients, but P, K rates limited to 50% of adjusted quantity (V50);
7. NPK – basic set of nutrients, full rate of adjusted quantity of nutrients (V100);
8. $NP^{*}K$ – basic set of nutrients, as in the W100 variant, but P was applied as partially acidulated phosphoric rock (V100P).

The preceding crop for sugar beet (variety *Kassandra*) was winter wheat. The main rates of phosphorus and potassium were calculated annually based on the expected yield of storage roots (60 t ha^{-1}) and the current soil P and K fertility for the NPK treatment. The actually applied rates of both nutrients followed the experimental design. The rate of fertilizer nitrogen was also calculated annually taking into account three components; i) content of soil mineral nitrogen in the layer 0.9 m, ii) the expected yield, and iii) unit nitrogen accumulation of four kg N t^{-1} (taproots + respective amount of tops). It amounted to 150 kg ha^{-1} in 2001 and 2003 and 120 kg ha^{-1}. All basic fertilizers and the first rate of nitrogen equal 80 kg N ha^{-1} were applied in spring before seedbed preparation. The remaining nitrogen rate was top-dressed at the stage of 3(5) leaf.

For purposes of this particular study, eight plants were sampled (1 m^2) on eight consecutive dates during the sugar beet growth, counting days after sowing (DAS): 40, 55, 77, 92, 113, 134, 155, 175. On each date, every plant sample was divided into sub-samples of leaves and the storage root, and then dried (65°C). The results were expressed on the dry matter (DM) basis. Nitrogen concentration in plant parts was determined by standard macro-Kjeldahl procedure. Nitrogen accumulation (yield) at each sampling date was calculated based on its concentration and dry matter yield of particular parts of sugar beet plants.

The growth analysis procedure was applied to determine the dynamics of nitrogen accumulation during the growing season. Two parameters were applied, determined separately for leaves and taproots and also for the total N uptake by sugar beet canopy. The first parameter, termed as Crop Nitrogen Uptake Rate (CNUR), was calculated from the formula:

$$CNUR = \frac{N_{a2} - N_{a1}}{T_2 - T_1} \cdot$$

The second growth parameter, the Relative Rate of Nitrogen Uptake, was calculated using the formula:

$$RRNU = \frac{LnN_aW_2 - LnN_aW_1}{T_2 - T_1},$$

where:

N_{a2}, N_{a1} – yield of accumulated nitrogen in two consecutive samplings; kg ha^{-1};

T_2, T_1 – two consecutive sampling dates, days after sowing (DAS).

The experimentally obtained sets of data were subjected to conventional analysis of variance, using the computer program Statistica 7. The least significant differences (LSD at $P = 0.05$) were calculated to establish the significance of means for each factor or their interactions. Simple regression was applied to estimate the strength of relationships between some plant characteristics.

RESULTS AND DISCUSSION

Leaves

Nitrogen accumulation (N_a) in leaves significantly depended on the tested fertilizing variants, but at the same time showed significant year-to-year variability (Table 1). The highest effect of the annual weather fluctuation occurred at early stages of the growth. At the stages BBCH 17 and 43, coefficients of variation were 83% and 43%, respectively. These two stages

Table 1

Statistical evaluation of main factors affecting nitrogen accumulation in sugar beet leaves during the growing season (kg ha^{-1} d.m.)

Factors	Level of factor	Days after sowing, DAS							
		40	57	77	92	113	134	155	175
Experimental variants (V)	control	2.79	8.04	19.36	53.9	57.76	73.94	76.7	78.29
	PK	3.63	11.18	30.13	64.2	65.08	69.45	69.3	79.03
	KN	6.99	30.80	64.88	127.4	133.6	105.4	109.1	132.0
	PN	7.10	25.63	59.57	99.7	112.4	114.8	117.5	118.9
	W25	6.10	31.41	73.07	124.2	123.6	110.5	121.1	135.3
	W50	7.61	32.38	67.94	128.9	115.8	103.2	106.9	123.0
	W100	8.72	32.33	63.70	112.8	135.0	125.9	104.4	117.9
	W100P	8.41	32.10	70.31	138.6	118.1	130.4	105.4	130.0
$LSD_{0.05}$		0.75	4.30	8.25	15.3	14.55	13.9	12.05	16.25
Years (Y)	2001	8.47	18.29	51.25	134.7	144.2	127.6	111.9	119.5
	2002	6.65	49.25	82.49	98.3	90.1	86.6	99.6	131.1
	2003	4.14	8.91	34.62	85.6	88.7	98.4	92.4	92.4
F-factor for years		88.3***	252.6***	91.6***	29.5***	50.3***	24.4***	7.2**	77.1***
F-factor for years and variants		5.43***	7.68***	4.55***	2.26*	1.67 n.s	2.53**	2.71**	1.85*

*, **, *** – probability levels of 0.05; 0.01; 0.001; n.s. – non significant

are critical for sugar beet plant development and yielding, as they are responsible for efficiency of solar-energy use (Malnou et al. 2006). The calculated coefficients clearly indicate differences in the nitrogen uptake rate by growing plants. The general trend of nitrogen accumulation in leaves during the growing season was progressive, following the quadratic regression model:

1. 2001: $N_a = -0.014\ DAS^2 + 3.97\ DAS - 142.7$ for $R^2 = 0.84$ and $N_{aop} = 142$ DAS
2. 2002: $N_a = -0.007\ DAS^2 + 2.12\ DAS - 53.76$ for $R^2 = 0.85$ and $N_{aop} = 151$ DAS
3. 2003: $N_a = -0.009\ DAS^2 + 2.61\ DAS - 98.23$ for $R^2 = 0.92$ and $N_{aop} = 145$ DAS

The day of the maximum N accumulation (N_{amax}) in leaves did not show high year-to-year differences. In 2001 and 2003, it occurred in the second decade of September, but in 2002, it took place one week later. However, the N_{amax} showed substantial seasonal differences, amounting to *ca* 138, 100 and 107 kg N ha^{-1}, respectively.

The effect of the tested fertilizing variants on N_a in sugar beet leaves was significant at each stage of plant sampling. At stage BBCH 14, four homogenous groups of variants are distinguishable, presented below in the decreasing order:

V100, V100P > V50, PN = KN, V25 > PK, control

This order was transient and changed considerably from the stage of BBCH 17 onwards, when the whole population of variants can be regrouped as follows:

V100, V100P, V50, V25, KN > PN > PK, control.

These groups dominated to the mid-season, characterized by the highest absolute rate of total biomass growth (Grzebisz et al. 2012). One of the most important observations about the sugar beet response to nutrient application appeared in the PN variant, i.e., in which potassium was omitted from the fertilizing program. Plants grown without fresh supply of potassium gathered significantly much more nitrogen in leaves in comparison to treatments without nitrogen, but at the same time far less than those fertilized with potassium. This phenomenon recurred at the final phase of sugar beet growth. The difference indirectly underlines the importance of potassium in the processes of nitrogen uptake (Marschner et al. 1995). However, the stimulating effect of potassium, as in the NK case, on the yield-forming effect of nitrogen taken up by beet plants is a controversial matter. High accumulation of nitrogen in leaves at harvest is related to its high concentration in the storage root, which depresses its technological quality (Hoffmann 2006).

The quadratic pattern of N accumulation in sugar beet leaves is typical, but the observed differences among the fertilizing variants can be explained better by the growth analysis procedure. The first parameter, the crop nitrogen uptake rate (CNUR), informs us about the absolute rate of nitrogen accumulation in sugar beet canopy during the growing season. In order to present typical trends, three out of the eight tested variants were selected, i.e., VPK, V25 and V100P. The first one, representing the treatment without nitrogen, showed the highest (except the absolute control) year-to-year variability of harvested yields of storage roots (average yield of 54.4 Mg ha^{-1} and CV = 34.4%). The second one, characterized by the application of 25% of the recommended rate of P and K, showed both the highest average yield of beets (71.8 Mg ha^{-1}) and the lowest CV (9.9%). The third variant, comprising full amounts of recommended nutrients, showed a high yield of storage roots (72.4 Mg ha^{-1}) but almost a three-fold higher CV (+ 29%) than the V25 variant (not all data are not reported in the paper, but details are available from the authors).

Patterns of the in-season CNUR courses were much more dependent on the year-to-year weather variability than on the fertilizing variant (Figure 1a,b,c). In 2001 and 2003, patterns of the nitrogen accumulation rate in sugar beet leaves were very similar, irrespective of the treatment (Figure 1a and c). In the first part of the season, the CNUR increased exponentially, reaching the top at 92 DAS. Since 92 DAS onwards, a sudden, exponential drop was observed, demonstrating however a secondary, nutrient-specific increase. In the second season, in 2002, the elevation of the N rate uptake occurred much earlier in the nitrogen fertilized variants, i.e., at the stage of BBCH 17. The effect of the weather on the seasonal CNUR course is best presented for the V100P variant. The highest nitrogen uptake rate, irrespective of the stage of sugar beet growth, was *ca* 8, 6, and 4 kg N ha^{-1} d^{-1} in 2001, 2003, 2002, respectively (Figure 1c). The recorded differences reflect, albeit only partly, the importance of $CNUR_{max}$ for the

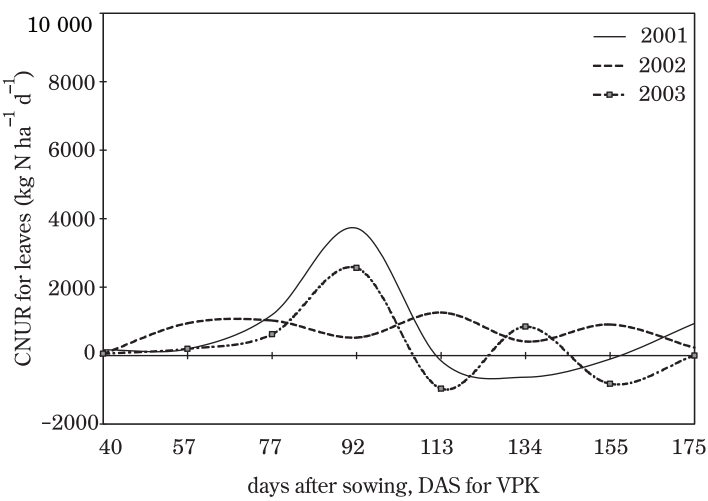

Fig. 1a. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet leaves, PK treatment

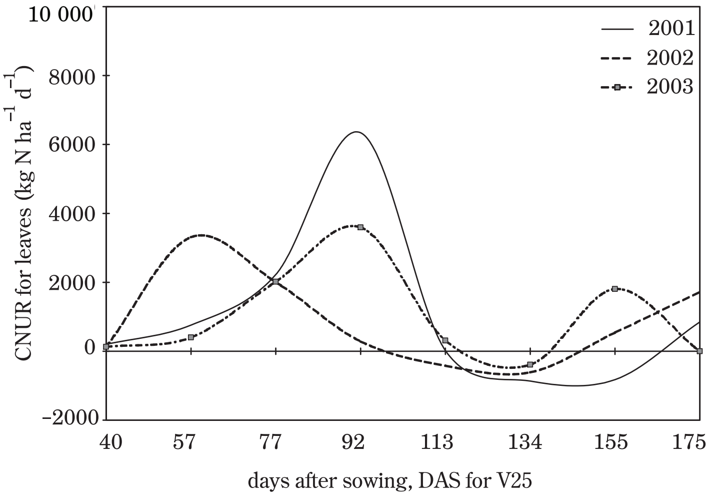

Fig. 1b. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet leaves, V25 treatment

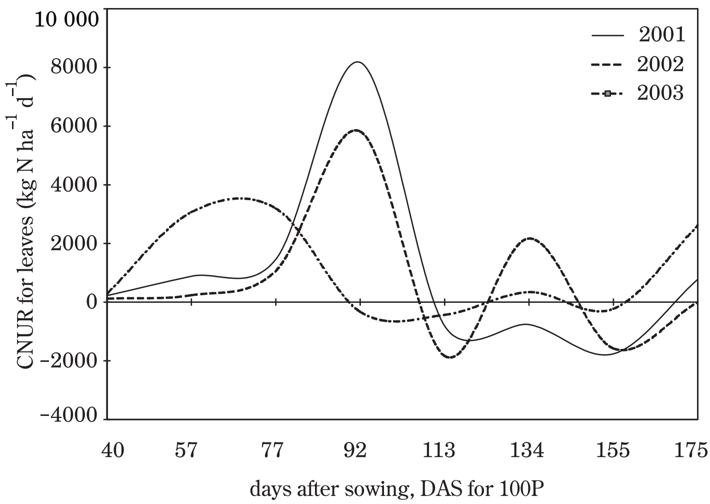

Fig. 1c. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet leaves, V100P treatment

final yield of storage roots. They also indicate that sugar beet plants under water stress are able to compensate the rate of storage root growth.

The second-growth parameter taken into account in this study is the relative rate of nitrogen uptake (RRNU). The course of the developed curves can be described by some attributes such as i) the average value for the whole season, ii) the maximum RRNU value, the DAS of $RRNU_{max}$ elevation (Table 2). The general pattern of this growth parameter was very similar in the first part of the season. In 2001 and 2003, the minor peak of the RRNU intake appeared at early stages of sugar beet growth, i.e., at the

Table 2

Statistical overview of relative rate of nitrogen uptake (RRNU) by sugar beet during the growing season

Statistical parameters		Leaves			Storage roots			Total		
		VPK	V25	V100P	VPK	V25	V100P	VPK	V25	V100P
2001										
Max	kg kg^{-1} d^{-1}	0.32	0.24	0.34	0.27	0.28	0.28	0.32	0.34	0.29
DAS_{max}		92	92	65	92	92	92	57	92	92
Average		0.13	0.11	0.14	0.19	0.20	0.20	0.21	0.17	0.17
SD*		0.12	0.11	0.13	0.06	0.06	0.06	0.06	0.12	0.12
CV**	%	94	93	95	34	30	31	30	72	70
2002										
Max	kg kg^{-1} d^{-1}	0.26	0.28	0.28	0.27	0.29	0.29	0.32	0.33	0.34
DAS_{max}		57	57	57	92	92	92	92	92	92
Average		0.20	0.16	0.13	0.16	0.17	0.17	0.19	0.20	0.17
SD		0.05	0.11	0.12	0.09	0.09	0.09	0.6	0.10	0.12
CV	%	27	71	92	55	54	54	30	53	73
2003										
Max	kg kg^{-1} d^{-1}	0.31	0.31	0.33	0.29	0.31	0.30	0.32	0.33	0.34
DAS_{max}		92	92	92	92	92	92	92	92	92
Average		0.13	0.16	0.13	0.16	0.15	0.20	0.16	0.17	0.17
SD		0.12	0.12	0.13	0.09	0.12	0.07	0.12	0.12	0.12
CV	%	95	73	95	57	76	34	73	72	73

*standard deviation, **coefficient of variation

stage of BBCH 17. The second, major one, took place at 92 DAS (Figure 2). The effect of the fertilizing variants on the average RRNU values was relatively low, achieving the highest values in 2002. For all the fertilizing variants and years, the RRNU showed high in-season variability, as described by coefficients of variation. This was, nevertheless, an attribute of the second part of the season and treatments with nitrogen. The reported recovery of the N uptake corroborates the thesis of FRECKLETON et al. (1999) of the importance of N fertilization in controlling water shortage. The main reason of certain inconsistency of the coefficient of variation was the weather variability in August and September, in turn affecting the uptake of fertili-

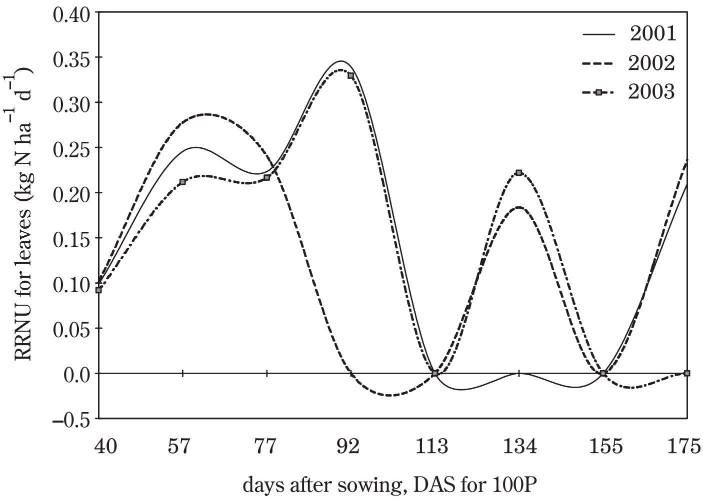

Fig. 2. Effect of the full sugar beet fertilizing on the dynamics of relative nitrogen accumulation rate in sugar beet leaves, V100P treatment

zer nitrogen. This outcome is in agreement with KENTER et al. (2006), who stressed the importance of the course of weather in these two months for the final yield of storage root yields.

Storage roots

The effect of the fertilizing variants on nitrogen accumulation in storage roots was significant, but at the same time year-dependent for the most stages in the growing seasons (Table 3). As in the case of leaves, the course of these attributes during the growing season can be described by year-specific regression models:

1. 2001: N_a = 0.967 DAS – 45.56 for R^2 = 0.99;
2. 2002: N_a = -0.00013 DAS^3 + 0.04 DAS^2 - 3.12 DAS + 66.00 for R^2 = 0.998;
3. 2003: N_a = -1.017 DAS – 52.49 for R^2 = 0.96.

In the first and third growing season, as results from the developed linear models, nitrogen accumulation in storage roots was continuously progressing. This pattern of N in-season accumulation indirectly underlines an ample supply of nitrogen to beet plants from both soil and fertilizer resources until the end of the growing season. This uptake scenario is possible because the storage root can continue its growth for more than 175 days, as occurred in 2001 (MAELANDER et al. 2003). The linear model of N accumulation can be therefore considered as positive, provided that it results in a simultaneous increase in yield of storage root. This happened in 2001 but not in 2003. For example, in 2001, the yield of storage roots for the 100 P variant slightly exceeded 95 t ha^{-1}, whereas in 2003 amounted only to 60 t ha^{-1}.

Table 3

Statistical evaluation of main factors affecting nitrogen accumulation in sugar beet storage roots during the growing season (kg ha^{-1} d.m)

Factors	Level of factor	Days after sowing, DAS							
		40	57	77	92	113	134	155	175
Experi-mental variants (V)	control	0.08	1.27	6.75	20.06	37.70	54.02	60.02	76.0
	PK	0.12	2.21	8.68	23.58	38.31	62.52	69.13	80.6
	KN	0.37	5.19	18.07	46.40	75.13	86.28	107.41	114.0
	PN	0.34	3.49	16.51	36.40	66.54	97.10	104.73	113.6
	W25	0.37	5.56	18.68	44.49	78.02	79.46	120.19	114.8
	W50	0.34	5.66	17.55	46.77	75.88	86.12	99.84	148.4
	W100	0.40	6.09	15.21	43.97	77.40	92.91	109.78	136.3
	W100P	0.38	5.20	21.10	47.49	62.54	98.04	112.89	142.9
$LSD_{0.05}$		0.06	0.81	2.73	5.34	7.79	8.60	13.10	15.70
Years (Y)	2001	0.26		24.32	46.50	58.76	81.69	101.4	130.6
	2002	0.38	1.95	13.44	32.41	60.93	78.41	93.9	86.2
	2003	0.27	4.31	8.20	37.03	72.13	86.05	98.7	130.1
F-factor for years		14.9***	92.7***	96.4***	19.2***	9.00***	2.1 n.s	0.88	28.3***
F-factor for years and variants		0.68	4.7***	6.9***	2.8**	1.9*	1.9*	2,5**	1.2 n.s

*, **, *** – probability levels of 0.05; 0.01; 0.001; n.s. – non significant

Quite a different pattern of nitrogen accumulation was recorded in 2002. The developed regression model indicates occurrence of some factors limiting the N uptake rate during the season. Calculating the first derivative, the transition day of nitrogen uptake rate can be fixed. In this case, it occurred at 103 DAS, i.e. it took place at the end of the third decade of July. The main cause of the decreased rate of N accumulation in storage roots was water shortage, which reduced the rate of nitrogen uptake. This pattern of N accumulation can be considered as positive provided that yield of storage roots follows the same course or increases.

The effect of the fertilizing variants on the nitrogen accumulation course showed the highest variability and dependence on the actual weather conditions, but limited to the first part of the season. Again, the most interesting is the NP variant. Plants grown without fertilizer potassium accumulated far less until 113 DAS than in the other N fertilized variants. At harvest, the nitrogen status in storage roots can provide much useful information. All the fertilizing variants, according to LSD, can be divided into three distinctive groups based on the quantity of accumulated N:

V50, V100, V100P > V25, VKN, VPN > VPK, control.

The order of the variants is simply related to rates of applied P and K fertilizers. Therefore, it can be concluded that rates of both nutrients below

50% of the recommended rate do not guarantee to cover sugar beet requirements for nitrogen. This conclusion is true, assuming that the growth conditions allowing full exploitation of the sugar beet yielding potential. Its achievement depends, however, on the weather course during the middle and second part of the season (Figure 3a, b). Sugar beet plants could compensate the rate of nitrogen accumulation in storage roots during the second part of the season, in turn stimulating the rate of both canopy and storage root growth (Grzebisz et al. 2012). This finding is contrary to the observation reported for sugar beets grown in Britain and made by Malnou et al. (2008). These authors did not find any significant effect of late-summer, compensatory supply of N on beet on sugar yield.

The conducted growth analysis showed high, but inconsistent variability of the nitrogen accumulation rate in storage roots (Figure 3a, b). The general pattern of CNUR showed a sinusoidal-like course. It inconsistency was both year- and nutrient-specific. Plants grown on plots fertilized with 25% of the recommended P and K rates, showed high recurring peaks, which took place at 92 and 155 DAS in 2003 and at 113 and 155 DAS in 2002. For comparison, in 2001 plants grown on the 100P plot showed a constant rate of N accumulation from the stage of BBCH 43 onwards. This pattern of growth was a prerequisite of a significantly high yield of storage roots. However, as presented in the Figure 3b, the in-season variable pattern of N accumulation can be considered as an attribute of a high-yielding sugar beet plantation. The fully fertilized variants showed a multi-elevation pattern of the CNUR course. The highest yield of storage roots can be related to a very fast rate of N accumulation in the early stages of growth, followed by secondary and even tertiary elevations. Any factor delaying the rate of N accu-

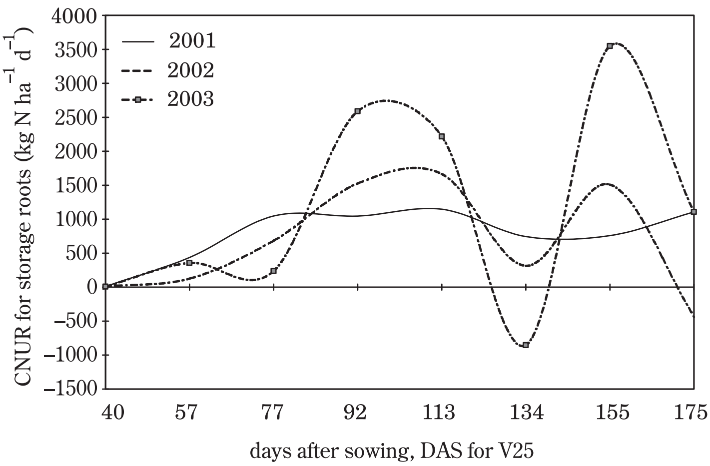

Fig. 3a. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in storage roots, V25 treatment

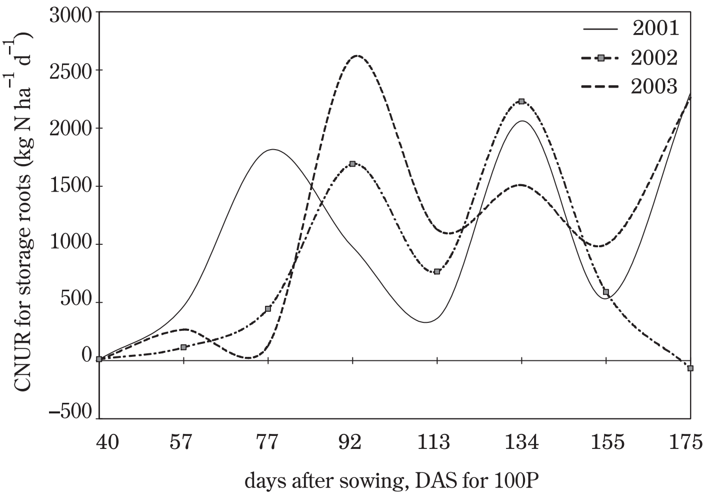

Fig. 3b. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in storage roots, V100P treatment

mulation in the storage root in the early stages of growth negatively affects its final yield, as occurred in 2002. The pattern of N accumulation dynamics, as described for the 100P variant in 2001, fully corroborates the thesis presented by Boiffin et al. (1992), who assumed that any factor disturbing the rate of canopy growth at the early stages of sugar beet growth negatively affected the interception of solar radiation by the sugar beet canopy, thus slowing down the rate of plant growth due to inferior utilization of solar energy. It can be therefore concluded that any factor retarding the N uptake accumulation in the storage root during the early stages of sugar beet growth negatively affects its yield (Malnou et al. 2006). It has been documented that nitrogen accumulated in the young storage root is important for the development of parenchyma rings, a prerequisite of its potential storage size for sugar accumulation (Bell et al. 1996).

The general pattern of the relative rate of nitrogen accumulation (RRNA) in the storage root was highly consistent in years and fertilizing variants (Table 2, Figure 4). S a rule, plants achieved $RRNA_{max}$, which ranged from 0.27 to 0.31 kg N kg^{-1} d^{-1}, at 92 DAS. The average RRNA, however, was slightly affected by the annual weather course, being much lower in 2002 and 2003. The main reason for high in-season RRNA variability, as indicated by the coefficient of variation, was its inconsistency in the second part of the season. It was both nutrient- and year-specific.

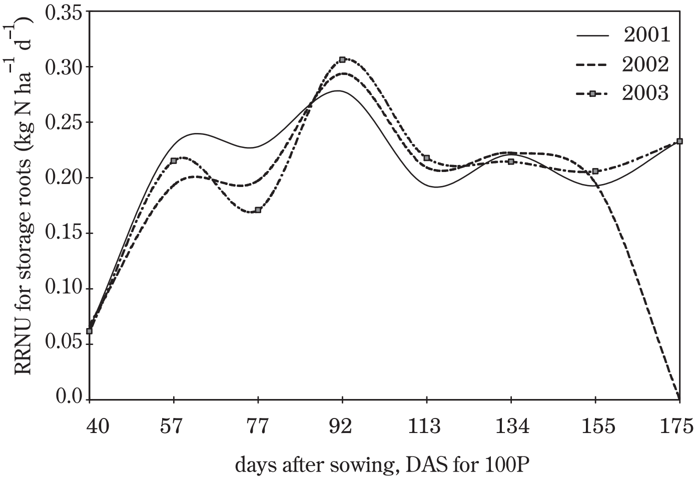

Fig. 4. Effect of the full sugar beet fertilizing on the dynamics of relative nitrogen accumulation rate in storage roots, V100P treatment

Total nitrogen uptake

The total nitrogen accumulation in sugar beet canopy during the growing season showed a significant response to the tested fertilizing variants. However, it was distinctly modified by the course of weather in each stage of plant growth except at harvest (Table 4). The strongest effect of the weather was manifested in the early stages of sugar beet development. The general pattern of total N accumulation in beets during the growing season can be described by two regression models. In 2001, it followed a quadratic function but in 2002 and 2003, it was described by a linear one, as presented below:

1. 2001: $N_{at} = -0.014\ DAS^2 + 4.741DAS - 177.8$ for $R^2 = 0.93$ and $DAS_{op} = 169$;
2. 2002: $N_{at} = -\ 1.469\ DAS - 28.37$ for $R^2 = 0.95$;
3. 2003: $N_{at} = 1.757\ DAS - 67.34$ for $R^2 = 0.93$.

The models of N accumulation during the growing season indirectly indicate completely different growing conditions in 2001 in comparison to the other years. In 2001, sugar beet plants could fully exploit soil and fertilizer N resources, reaching the *nitrogen saturation* status. This is verified by the maximum N uptake of 223.6 kg N ha^{-1}, achieved at 169 DAS. The presented model coincides with the maximum yield of storage roots. Therefore, the quadratic model of N accumulation by sugar beet plants throughout the season can be considered as optimal for the maximum N productivity. In the other two years, the linear model of in-season N accumulation dominated, in turn underlying the *unsaturated status* of nitrogen management by beet plants. The term simply means that plants could accumulate high amounts of nitrogen, but did not convert them into a respective biomass of

Table 4

Statistical evaluation of main factors affecting total nitrogen accumulation in sugar beet during the growing season (kg ha^{-1} d.m.)

Factors	Level of factor	Days after sowing, DAS							
		40	57	77	92	113	134	155	175
Experimental variants (V)	control	2.87	9.30	26.11	73.96	95.5	128.0	136.7	154.3
	PK	3.75	13.39	38.81	87.76	103.4	132.0	138.5	159.7
	KN	7.36	35.99	82.95	173.9	208.7	191.7	216.5	246.0
	PN	7.45	29.12	76.07	136.1	178.9	211.9	222.2	232.5
	W25	6.48	36.97	91.75	168.7	201.6	190.0	241.3	250.0
	W50	7.95	38.03	85.49	175.7	191.7	189.3	206.7	271.3
	W100	9.12	38.42	78.91	156.8	212.4	218.8	214.2	254.3
	W100P	8.79	37.31	91.41	186.1	180.7	228.4	218.3	272.9
$LSD_{0.05}$		0.77	4.84	9.70	17.95	17.94	18.83	20.48	20.25
Years (Y)	2001	6.91	55.99	106.8	144.8	148.9	168.3	200.9	250.0
	2002	8.85	20.24	64.7	167.1	205.1	206.0	205.9	217.3
	2003	4.40	13.21	42.8	122.6	160.8	184.5	191.1	223.0
F-factor for years		88.2***	238***	112.7***	16.3***	28.9***	10.7***	1.4 n.s	45.4***
F-factor for years and variants		5.2***	7.0***	5.9***	2.5**	1.9*	2.5**	3.2***	1.4 n.s.

*, **, *** – probability levels of 0.05; 0.01; 0.001; n.s. – non significant

beets. As a result, the harvested yields of storage roots were much lower than in 2001. Therefore, this model presents a sub-optimal model of N management by sugar beet canopy.

Nitrogen accumulation (N_a) during the course of a growing season was stage-to-stage variable. Its seasonal fluctuation, induced by the weather course, occurs mainly between the treatments fertilized with nitrogen. The applied index, determined at sugar beet harvest, known as nitrogen use efficiency (NUE), confirms high year-to-year N_a variability (Figure 5). The average NUE values were 72%, 48%, 62% for 2001, 2002, and 2003, respectively. What is even more interesting is the nutrient-induced variability of NUE, as described by the coefficient of variation (CV, %):

VPN (9.9) < VKN (15.1) < V25 (20.9) < V100 (22.8) < V50 (31.5) < V100P (37.3).

The most stabile value of NUE, but at the same time the lowest among the fertilizing variants, is attributed to the PN treatment (55.5%), i.e., without potassium. The importance of this particular nutrient for N uptake is supported by the fact that efficiency of N fertilizer, as found for the KN variant, was 10% higher (65.1%). The third group of variants consists of two treatments, i.e., V25 and V100. For both, the NUE increased slightly above 70%, but at the same time its seasonal variability exceeded 20%. The fourth group, characterized by the highest variability of both indices, i.e., the NUE (> 81%) and CV (above 30%), comprises V50 and V100P variants. The impact

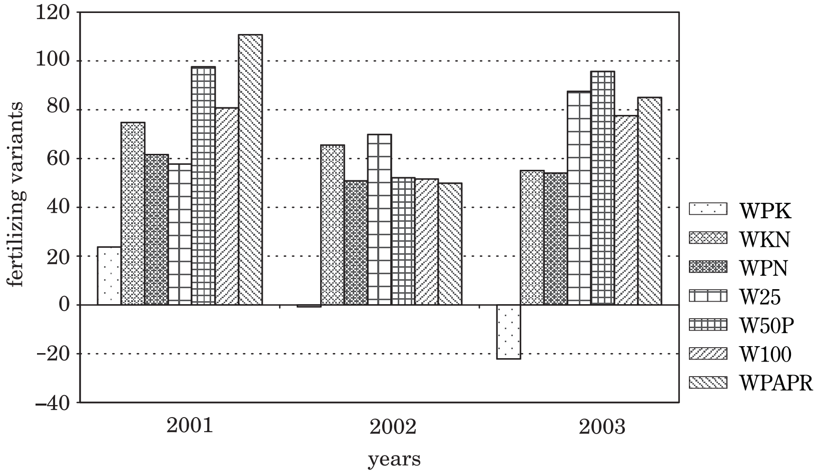

Fig. 5. Effect of differentiated fertilizing variants on nitrogen use efficiency in three consecutive growing seasons

of full supply of nutrients on nitrogen recovery was extremely high, both in the wet year 2001, when it approached 100% and in the dry year 2003.

The above variability of NUE indirectly reflects high dynamics of nitrogen accumulation in sugar beet plants throughout the season. The in-season course of the crop nitrogen uptake rate (CNUR) for total N showed high variability in response to both years and applied nutrients. The effect of variable weather conditions allows us to distinguish two main patterns of N uptake, as presented in Figure 6a-c. In 2001 and 2003, sugar beet canopy

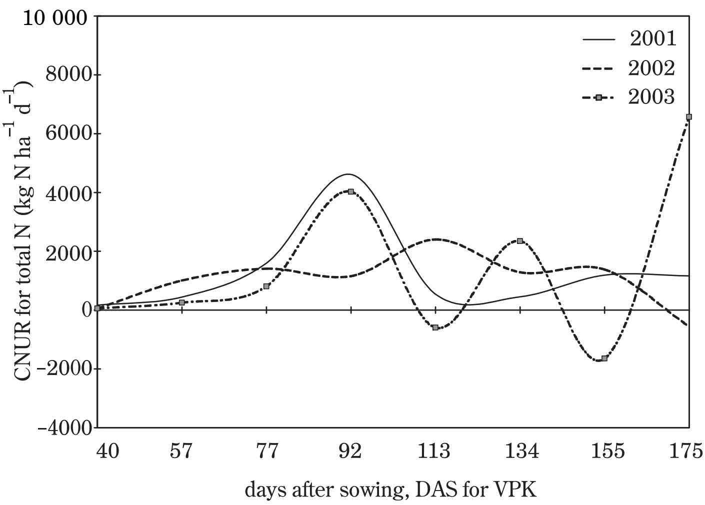

Fig. 6a. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet canopy, PK treatment

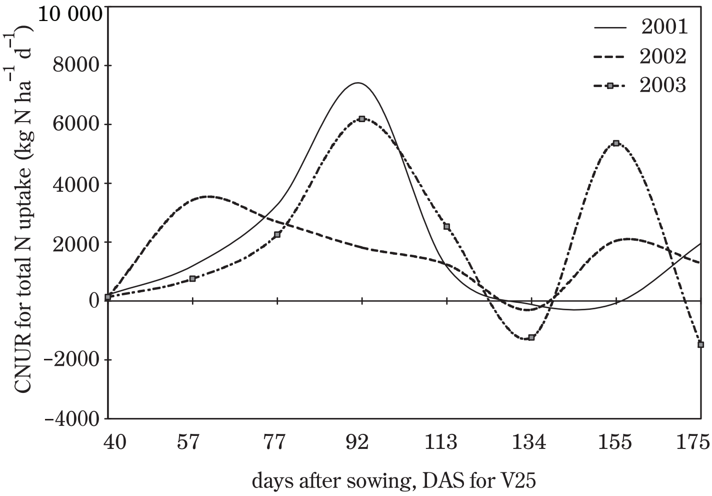

Fig. 6b. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet canopy, V25 treatment

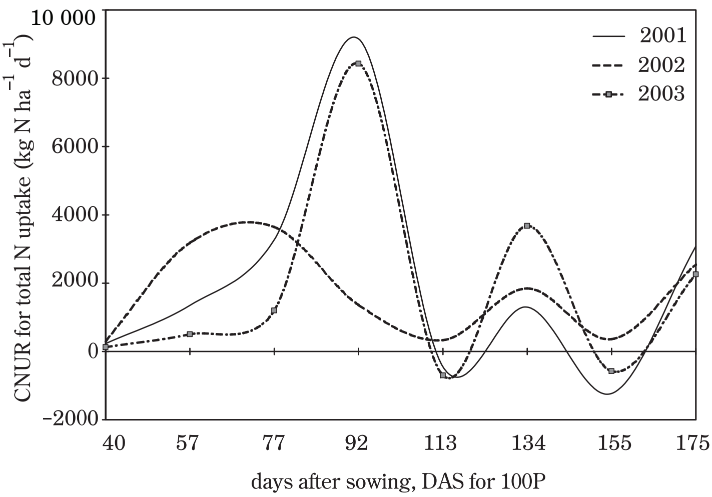

Fig. 6c. Effect of fertilizing variants on the dynamics of absolute nitrogen accumulation rate in sugar beet canopy, V100P treatment

achieved the maximum CNUR at 92 DAS, but in 2002 it happened five weeks earlier, i.e. at BBCH 17. This year-induced difference in the nitrogen accumulation rate was combined with a significant effect of the fertilizing variants. Plants fertilized with 25% of the recommended rate of PK but with a full rate of N accumulated N at the maximum rate of 6 kg N ha^{-1} d^{-1}, but those fertilized with a full PK rate could take up $^1/_3$ more nitrogen on a daily basis, i.e., 8 kg N ha^{-1} d^{-1}. For comparison, beet plants grown in 2002 did not exceed $CNUR_{max}$ of 4 kg N ha^{-1} d^{-1}. Therefore, it can be concluded that in 2002 sugar beet plants experienced nitrogen stress immediately before the period of the highest natural rate of canopy growth. An insufficient supply of nitrate-nitrogen to plants in the early stages of their growth is to a large extent related to an insufficient supply of soil potassium, as was confirmed by the in-season N accumulation in beets grown in the PN treatment (Table 4). As pointed out by MARSCHNER et al. (1996), deficient supply of potassium to growing plants negatively affects the rate of CO_2 fixation, in turn decreasing the size of beets leaves. We should be aware that this nitrate nitrogen temporarily lost is taken up by plants during the later stages of sugar beet growth, in turn disturbing the partitioning of assimilates and deteriorating the technological quality of storage roots (HOFFMANN 2005, POCOCK et al. 1990, WOJCIECHOWSKI et al. 2002).

Despite our expectations, the second-growth parameter, the relative rate of nitrogen uptake (RRNU), did not show high variability in response to the studied factors (Table 2, Figure 7). Sugar beet plants achieved the maximum RRNU generally at 92 DAS, i.e. covering the highest absolute rate of both leaves and taproot growth. As presented in Fig. 7, sugar beet canopy showed a secondary in-growth rate of nitrogen uptake, which for the PK limited treatments in years with drought (2002, 2003) took place three weeks earlier than in wet 2001 (Figure 7a). For the variants with a full supply on both nutrients, the RRNU curves showed the same course, irrespective of

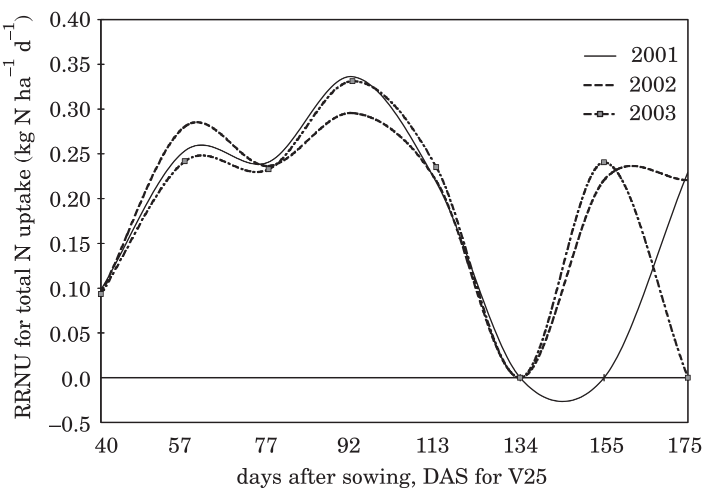

Fig. 7a. Effect of fertilizing variants on the dynamics of relative nitrogen accumulation rate in sugar beet canopy, V25 treatment

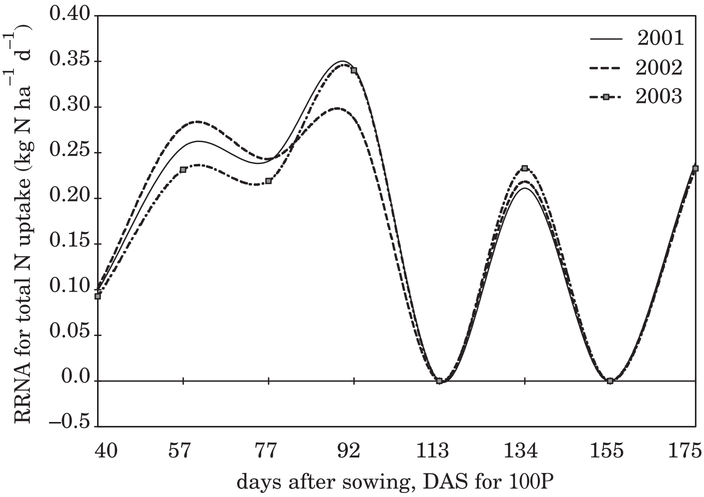

Fig. 7b. Effect of fertilizing variants on the dynamics of relative nitrogen accumulation rate in sugar beet canopy, V100P treatment

the weather conditions (Figure 7b). However, in the first year of the experiment, plants' response focused on storage root yield increase, whereas in the years with water stress, the secondary in-growth of leaves was more strongly affected.

CONCLUSIONS

1. The general pattern of nitrogen accumulation in leaves during the course of the growing season is well described by the quadratic regression model. The course of the weather significantly affects the maximum of N accumulation.

2. The crop nitrogen uptake rate for leaves is slightly variable in the first part of the sugar beet growing season, but, but becomes significantly varied in the second one.

3. The $CNUR_{max}$ for leaves reflects fairly well the yielding potential of sugar as affected by the weather course and level of applied nutrients. Phosphorus and potassium rates below 50% of the recommended rate do not ensure that the storage root requirements for nitrogen are covered.

4. As a rule, the nitrogen accumulation in leaves and the storage root was lower in plants without fertilizer potassium.

5. The developed patterns of absolute and relative uptake rate of nitrogen shows compensatory uptake of N from its soil resources in the second

part of the season. However, its effect on the yield of storage roots was inconsistent. Under ample water and nutrient supplies, it could be considered as a factor allowing complete exploitation of the yielding potential of sugar beets.

6. The quadratic model of the total nitrogen accumulation in sugar beet canopy throughout the

season indicates high efficiency of both soil and fertilizer nitrogen taken up by plants.

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