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# IMPACT OF NITROGEN CONCENTRATION VARIABILITY IN SUGAR BEET PLANT ORGANS THROUGHOUT THE GROWING SEASON ON DRY MATTER ACCUMULATION PATTERNS

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Abstract

Nitrogen concentration ($N_c$) in leaves, in each stage of sugar beet development, is the major factor stimulating the accumulation of dry matter in leaves, which in turn affects the dry matter concentration in storage roots and, consequently, determines sugar beet yields. This thesis was verified based on the data obtained from a static field 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 the recommended amount of all basic nutrients (NPK, $NP^{*}K$, $P^{*}$ – P in the form of PAPR). Nitrogen concentrations in leaves and storage roots of sugar beet tended to decline during the growing season, but the former tendency adhered to a linear-plateau model while the latter corresponded to an exponential one. This discrepancy, revealed in the second part of the season, can be considered as an indicator of a high yield of storage roots, especially in years favorable for sugar beet vegetation. The growth analysis allowed us to determine the time and the maximum rate of canopy and storage root growth during the season. Irrespective of the fertilizing variant, both organs of sugar beet reached the maximum rate of growth from 92 to 113 day after sowing (DAS). Plants grown under conditions of ample water and nutrient supply (2001) reached a three-fold higher rate of leaf growth than in dry years (2002, 2003). The storage root showed much smaller differences in the absolute rate of growth. However, the effect of fertilizing variants was stronger, especially from 92 DAS onwards. Trends of the relative growth rate for each of the two tested plant organs were very similar. The highest growth rate for both organs occurred in early stages of sugar beet development and then progressively declined. Nevertheless, only this growth parameter responded si-

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gnificantly during the season to the variability of $N_c$ in both sugar beet organs. The relationships showed that sugar beet plants could compensate the dry matter growth rate during early stages of sugar beet development, especially in years favorable for sugar beet growth. The impact of nitrogen concentrations in leaves on the relative storage root growth dynamics was curvilinear in 2001 but linear in the other years, i.e., the ones when droughts were frequent. At the same time, the relationship between $N_c$ and storage root fraction was always linear. This type of a relationship clearly demonstrates the natural conservatism of the storage root to its variable nitrogen concentration during the growing season.

Key words: sugar beet, nitrogen concentration, leaves, storage root, absolute and relative rate of growth.

# WPŁYW ZMIENNOŚCI KONCENTRACJI AZOTU W CZĘŚCIACH BURAKA CUKROWEGO W OKRESIE WEGETACJI NA WZORCE AKUMULACJI SUCHEJ MASY

## Abstrakt

Koncentracja azotu w liściach buraka cukrowego w każdej fazie rozwoju rośliny jest głównym czynnikiem wpływającym na tempo akumulacji suchej masy liści, tym samym na koncentrację składnika w korzeniu spichrzowym, a w konsekwencji kształtującym dynamikę jego wzrostu. Tak sformułowana teza została zweryfikowana na podstawie danych uzyskanych w doświadczeniu polowym, statycznym, prowadzonym w latach 2001-2003, z ośmioma wariantami nawozowymi: 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). W okresie wegetacji zawartość azotu w liściach i korzeniu spichrzowym buraka wykazywała trendy spadkowe, lecz ujawniające się odmiennie, odpowiednio jako model liniowo-plateau i potęgowy. Niezgodność ta, pojawiająca się w drugiej części sezonu, może być traktowana jako wskaźnik dużego plonu korzeni, zwłaszcza w latach optymalnych dla wegetacji buraka cukrowego. Zastosowana analiza wzrostowa pozwoliła określić termin i wartość maksymalnej szybkości wzrostu liści i korzeni w okresie wegetacji. Niezależnie od wariantu nawozowego, maksymalne wartości wzrostu obu organów wystąpiły w okresie od 92. do 113. dnia od siewu. Buraki cukrowe rosnące w warunkach optymalnego zaopatrzenia w wodę (2001) osiągnęły 3-krotnie większą szybkość wzrostu liści niż w latach z suszą (2002, 2003). W korzeniach spichrzowych wykazano znacznie mniejsze różnice wskaźnika, jakim jest absolutna szybkości wzrostu. Jednakże ujawnił się dużo większy wpływ wariantów nawozowych, zwłaszcza w drugiej części sezonu wegetacyjnego. Trendy przyrostu suchej masy, rozpatrywane oddzielnie dla obu organów buraka, były bardzo podobne. Maksymalne wartości wystąpiły w początkowym okresie wegetacji, podlegając następnie stopniowemu spadkowi. Jednakże tylko ten wskaźnik wzrostu wykazał istotny związek z koncentracją azotu w obu częściach buraka cukrowego. Zależności korelacyjne wykazały, że rośliny były w stanie kompensować szybkość wzrostu w początkowym okresie wegetacji, zwłaszcza w roku o optymalnym przebiegu pogody (2001). Wpływ koncentracji azotu w liściach na względną dynamikę wzrostu masy korzenia spichrzowego okazał się krzywoliniowy w roku 2001 i prostoliniowy w pozostałych latach (z częstymi suszami). Natomiast relacje między koncentracją azotu w korzeniu spichrzowym i jego udziałem w biomasie całkowitej buraka były zawsze liniowe. Ten model relacji podkreśla naturalny konserwatyzm korzenia spichrzowego w reakcji na zmienną koncentrację azotu w tej częsci rośliny w okresie wegetacji.

Słowa kluczowe: burak cukrowy, koncentracja azotu, liście, korzeń spichrzowy, absolutna i względna szybkość wzrostu.

# INTRODUCTION

In Europe, sugar beet (*Beta vulgaris* L.) is the only crop producing sugar in amounts ensuring the feasibility of technological processing. Over a large area, from northern France to eastern Poland, potential yields of this crop determined by climatic conditions are estimated in the range of 80-85 t $ha^{-1}$ (Supit et al. 2010). However, the harvested yields are much lower, ranging from above 70 t $ha^{-1}$ in France to below 50 t $ha^{-1}$ in Poland (FAOSTAT, 2011). There are two main reasons. One is the dominating weather in summer months, e.g. the impact of the continental climate (Jongman et al., 2006), experienced from the north-western to the eastern parts of the continent. Shortage of precipitation during summer months, which is responsible for frequently occurring droughts, is combined with high temperatures, significantly reducing yield of many crops, including sugar beets (Olesen et al. 2011, Supit et al. 2010).

The other significant factor shaping harvested yields of sugar beet is the fertility of soil under this crop. This term combines two soil attributes, namely the inherent soil fertility and the applied nutrient management. Sugar beet is highly sensitive to soil fertility, especially to the supply of potassium and phosphorus. The highest yields of storage roots are harvested from soils with a high potassium level. Potassium applied to currently grown crop during its critical stages of yield formation is generally considered as a factor alleviating, at least partly, the negative effects of water shortage (Cakmak, Kirkby 2008, Grzebisz et al. 2002, Milford et al. 2002).

Effects of both factors on sugar beet growth and yielding deserve much attention in regions like Central Europe, where sugar beet suffers severely from summer drought (Kenter et al. 2006). It is well recognized that under ample water supply sugar beet can fully exploit its yielding potential, provided that basic nutrients such as phosphorus and potassium do not retard the plant's growth (Freckleton et al. 1999, Hills et al. 1990, Herlichy 1992). However, the key nutrient affecting both the quantity of harvested yield of storage roots and their technological quality is nitrogen. It is well known that neither shortage nor excess of nitrogen at any stage of sugar beet growth affects negatively dry matter distribution and storage root quality (Hoffmann 2005). In Poland, sugar beet is grown on soils of different fertility, which affects the supply of nitrogen to growing plants. Therefore, nitrogen concentration in leaves, a plant organ responsible for $CO_2$ fixation, is considered as a factor significantly modifying the growth rate of both leaves and the storage root.

The primary objective of this study, which tested different levels of supplied nutrients such as N, P and K to sugar beet, was to determine patterns of dry matter accumulation in leaves and storage roots during a vegetative season. Another aim, in fact the key one, was to describe relationships between indices of dry matter accumulation in particular organs of sugar beet plants and nitrogen concentration in leaves and storage roots.

## MATERIAL AND METHODS

A static, field experiment was carried out on a private farm in Wieszczyczyn (52°02'N17°05'E) during three consecutive growing seasons 2001, 2002, 2003. The experiment was set up on soil originating from sandy loam underlined by loam, and classified as class IVa, good rye complex according to Polish soil valuation system, and light soil in the agronomical classification. The field trials, arranged in a single-factor design with four replications, consisted of eight treatments:

1. Control (absolute control, i.e. no applied fertilizers), (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 V100 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 taproots (60 t $ha^{-1}$) and 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 parameters: (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). 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 study, eight plants were sampled (1 $m^2$) on eight days of sugar beet growth after sowing (DAS): 40, 55, 77, 92, 113, 134, 155, 175. On each day, a plant sample was divided into sub-samples of leaves and a storage root, and then dried (65°C). The results were expressed on a dry matter (DM) basis. Nitrogen concentration in plant organs was determined by standard macro-Kjeldahl procedure.

The growth analysis procedure was applied to determine the Crop Growth Rate (CGR), but separately for leaves and taproots. For this study, the applied parameters are called Crop Leaves Growth Rate (CLGR) and Crop Root Growth Rate and (CRGR). The calculation was based on the formula:

$$CGR = \frac{W_2 - W_1}{T_2 - T_1}$$

Another growth parameter was the Relative Growth Rate (RGR), referred to as the Relative Growth Rate of Leaves (RGRL) and the Relative Growth Rate of Storage Roots (RGR-SR)for particular organs of sugar beet plants. It was calculated from the formula:

$$RGR = \frac{\ln W_2 - \mathrm{Ln} W_1}{T_2 - T_1}$$

where,

$W_2$, $W_1$ – yield of dry matter in two consecutive samplings (kg $ha^{-1}$);
$T_2$, $T_1$ – two consecutive sampling dates, days after sowing (DAS)

All data were subjected to conventional analysis of variance using a computer programme package Statistica 7. Simple regression was applied to estimate the strength of relationships between some plant characteristics.

## RESULTS AND DISCUSSION

### General growth conditions

The experimental field was located on light but productive soil originating from post- glacial loams. Its high, natural productivity depends on the loam underlying the topsoil. During each of the growing seasons, soil content of main available nutrients such as phosphorus, potassium and magnesium (soil + applied in fertilizers) was satisfactory for harvesting good yields of storage roots. Therefore, it was assumed that on plots receiving the full recommended rate of nutrients, the weather conditions were the key factor modifying the plants' growth and final yields of beets.

The evaluation of water management by a sugar beet plantation during the growing season should take into account four components, such as i) total water demand by the sugar beet plantation, ii) annual sum of precipitation, iii) soil water reserves, iv) distribution of precipitation over the growing season, with special emphasis to summer months. The total water requirement, based on sugar beet potential evaporation, in the region where the experiment was located is calculated at the level of 740 mm. The longterm average annual precipitation (1960-2010) is significantly lower, amounting to 600 mm. During the study, it fluctuated from *ca* 400 mm in 2003 to 650 in 2001. It can therefore be concluded that even in good years, sugar beet plant growth and yielding is negatively affected by water stress. The next important parameter of field water management takes into account soil water reserves, which are related to winter precipitation. For light soil, they are assessed at 146 to 210 mm for 1 m soil layer (*Regulation*... 2002). In the analyzed period, high soil water reserves appeared in 2001 and 2002 but not in 2003. For water management by a sugar beet plantation, precipitation in July and August is important. During the study, the reported amounts were as follows 100 mm in 2001, 85 mm in 2002 and 88 in 2003. This is much below the required level (180 mm). In 2002 and especially in 2003, sugar beet plants were exposed to frequent periods of water shortages. In 2003, the first drought lasted from March to the end of June. The second one, much more severe, occurred in August and September. It can therefore be concluded that in good years, like 2001, characterized by ample water supply, the sugar beet plant growth depended on a supply of nutrients, but in other years – on supply of water. This hypothesis was fully corroborated by the experimental data.

As a result of variable growth conditions for sugar beet, the final yields of storage roots showed a distinct and year-specific response to the tested fertilizing variants (detailed data available from the authors). Based on the conducted analysis of variance, five statistically homogenous groups of fertilizing variants were distinguished:

1) 2001:
   a) reduced, comprising three treatments: absolute control, VPK, VKN, (RE), (the average yield of storage roots for this group was 69.82 t $ha^{-1}$);
   b) limited supply of nutrients: VNP, V25, V50, (LI), (83.12 t $ha^{-1}$);
   c) full supply of nutrients: V100, V100P (FS), (94.35 t $ha^{-1}$).
2) 2002 and 2003:
   a) nitrogen control (absolute control, VPK), (C-N), (42.64 t $ha^{-1}$);
   b) fertilized with nitrogen (all other treatments), (N), (59.74 t $ha^{-1}$).

The detected differences between the analyzed fertilizing variants are high, clearly indicating much better growth conditions in 2001 than in the other years. In 2001, sugar beet achieved the full yielding potential, although limited by the supply of nutrients, i.e. nitrogen and phosphorus. This level of sugar beet production is possible only under ample water supply (Hills et al. 1990, Kenter et al. 2006). In the other years, yields were reduced by the limited supply of water, which minimized the importance of nutrients, except nitrogen.

## Trends of nitrogen concentration in sugar beet organs

As described in the introduction, nitrogen concentration ($N_c$) in leaves of sugar beet is the key factor shaping the crop canopy development, which in turn is decisive for solar energy fixation (Malnou at al. 2006). Most interest in total N concentration in the storage root focuses on its technological quality (Hoffmann 2005). However, this element can be considered as a reserve used by the storage root to prolong its further growth.

The present study showed, as expected, generally different trends of nitrogen concentration in both beet organs (Table 1). The average nitrogen concentration in leaves was much higher than in storage roots, but showed less variability with respect to the years and fertilizing variants. In the case of leaves, the highest in-season variability, as indicated by the value of the determination coefficient, did not exceed 20%. The general trend, averaged over years, can be best described by the linear-plateau model. During the first part of the season, N concentration ($N_c$) showed a declining trend, as presented below:

$$N_c = -0.025\text{DAS} + 5.13 \text{ for } R^2 = 0.99$$

In the second part of the season, from 113 DAS, it was on a constant, stabilized level of 23 g $kg^{-1}$ d.m.

In the storage root, the total N concentration was lower and showed slightly higher in-season variability than in leaves. The highest concentration occurred at the beginning and in the mid-season, when the lowest $N_c$ in leaves was reported. The general trend of nitrogen concentration in storage roots, averaged over years, can be described by the exponential function, as shown below:

Table 1

Variability of nitrogen concentration in sugar beet organs during the growing season – statistical overview

| Statistical parameters | Days after sowing | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 40 | 57 | 77 | 92 | 113 | 134 | 155 | 175 |
| Leaves | | | | | | | | |
| Average (g $kg^{-1}$) | 40.61 | 38.55 | 32.57 | 28.32 | 23.13 | 24.35 | 24.04 | 23.62 |
| SD* (g $kg^{-1}$) | 6.10 | 4.90 | 3.40 | 5.61 | 2.39 | 4.15 | 3.20 | 2.91 |
| CV** (%) | 15.01 | 12.72 | 10.42 | 19.79 | 10.33 | 17.04 | 13.29 | 12.32 |
| Min. (g $kg^{-1}$) | 27.14 | 27.09 | 25.62 | 20.27 | 17.95 | 16.26 | 18.98 | 18.63 |
| Max. (g $kg^{-1}$) | 48.45 | 45.31 | 39.09 | 38.11 | 26.90 | 32.09 | 30.33 | 31.66 |
| Storage root | | | | | | | | |
| Average (g $kg^{-1}$) | 19.50 | 15.12 | 11.19 | 9.52 | 8.66 | 8.51 | 7.36 | 6.41 |
| SD* (g $kg^{-1}$) | 4.97 | 1.95 | 1.48 | 1.34 | 1.51 | 1.37 | 0.99 | 1.02 |
| CV** (%) | 25.49 | 12.90 | 13.20 | 14.08 | 17.44 | 16.16 | 13.42 | 15.83 |
| Min. (g $kg^{-1}$) | 11.63 | 9.77 | 7.81 | 7.81 | 6.24 | 6.53 | 5.16 | 4.08 |
| Max. (g $kg^{-1}$) | 25.37 | 18.14 | 13.46 | 12.01 | 11.41 | 11.50 | 9.00 | 8.05 |

*standard deviation, **coeffcient of variation

$$N_c = 26.26\mathrm{DAS}^{-0.72} \text{ for } R^2 = 0.98$$

The detailed analysis of the developed regression models showed that the key differences in N concentration trends occurred in the second part of the season. The constant trend as reported for leaves versus the declining one for storage roots can be considered as an improved potential of sugar beet canopy for prolonged production of assimilates (WERKER et al. 1999). These results indicate that plants demonstrating this type of N management should produce higher yields of both storage roots and sugar.

## Patterns of dry matter accumulation in leaves

Dry matter yield of sugar beet plants throughout the growing season significantly depended on the fertilizing variants, whose effect was modified by the weather course in each year (Table 2). The interaction between the fertilizing variants and years was significant in three out of eight sampling dates. At harvest, however, irrespectively of the pattern of dry matter accumulation during the growing season, no significant year-to-year variability has been found.

The first estimated growth parameter describes the absolute growth rate of dry matter accumulation. In 2001, the developed curves showed almost the same shape during the course of the growing season (Figure 1). During the first period of the season, up to 92 day of vegetation (DAS), the rate

Table 2

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

| Factors | Level of factor | Days after sowing, DAS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 40 | 57 | 77 | 92 | 113 | 134 | 155 | 175 |
| Experimental variants (V) | control | 0.068 | 0.266 | 0.708 | 2.313 | 2.868 | 3.520 | 3.586 | 3.050 |
| | PK | 0.093 | 0.360 | 1.084 | 2.738 | 3.126 | 3.517 | 3.269 | 3.594 |
| | KN | 0.188 | 0.779 | 2.038 | 4.580 | 5.517 | 4.785 | 4.517 | 4.789 |
| | PN | 0.169 | 0.689 | 1.793 | 3.613 | 4.603 | 4.672 | 4.759 | 4.325 |
| | W25 | 0.171 | 0.854 | 2.264 | 4.283 | 5.641 | 4.460 | 4.724 | 4.597 |
| | W50 | 0.183 | 0.864 | 2.094 | 4.842 | 5.40 | 4.152 | 4.562 | 4.655 |
| | W100 | 0.210 | 0.857 | 2.023 | 3.924 | 5.423 | 5.029 | 4.406 | 4.475 |
| | W100P | 0.208 | 0.800 | 2.094 | 4.626 | 4.800 | 4.722 | 4.482 | 4.817 |
| $\mathrm{LSD}_{0.05}$ | 0.077 | 0.352 | 0.704 | 1.200 | 1.304 | 2.720 | 1.107 | 0.797 | Years (Y) |
| Years (Y) | 2001 | 0.181 | 0.463 | 1.495 | 5.171 | 6.028 | 5.982 | 5.181 | 4.109 |
| | 2002 | 0.204 | 1.365 | 2.764 | 3.922 | 4.126 | 3.597 | 4.309 | 4.505 |
| | 2003 | 0.098 | 0.222 | 1.027 | 2.501 | 3.727 | 4.018 | 3.375 | 4.307 |
| F-factor for years | | *** | *** | *** | *** | *** | *** | *** | n.s. |
| F-factor for years and variants | | n.s. | *** | * | n.s. | n.s. | n.s. | * | n.s. |

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

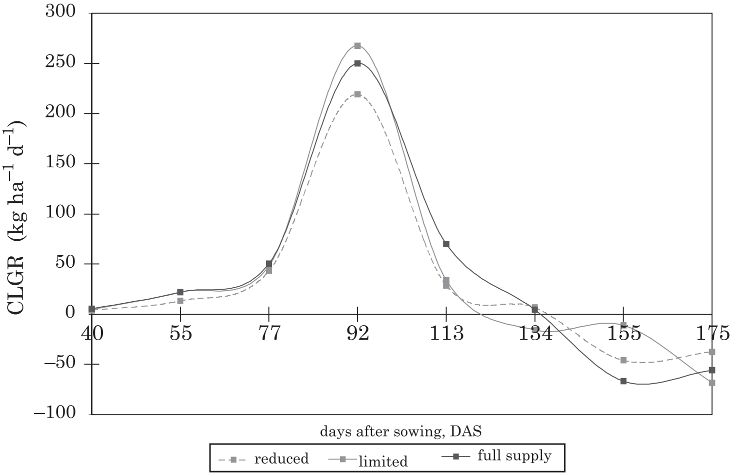

Fig. 1. Dynamics of the growth of dry matter in leaves against the background of nutrient system management, 2001 season

of the dry matter yield increase followed an exponential model, reaching the maximum. From 92 DAS on, the rate of dry matter accumulation showed a dramatic, variant-specific decline,. At this stage of the plant growth, the order of the variants was as follows:

limited > full supply > reduced.

In 2002 and 2003, patterns of dry matter accumulation by leaves were only seemingly similar to those found in 2001 (Figure 2). As in 2001, the top growth rate was reached on 92 DAS. However, on this specific day, the reported values were three-fold lower.

The second growth parameter, relative growth rate (RGR), generally confirmed the differences in dry matter accumulation in leaves. In 2001, the highest values, irrespective of the treatment, appeared at the beginning of vegetation (Figure 3). However, a secondary, but much smaller peak appeared on 92 DAS. The beginning of this secondary dry matter yield increase took place at BBCH 43 stage, when sugar beet plants reached the LAI of 3.0. This level of plant canopy is thought to fully exploit available solar radiation (MALNOU 2006). The secondary increase in sugar beet canopy can be only explained by an ample supply of soil nitrogen. At that particular period, the root system of sugar beet plants reaches the final size and enables plants to penetrate deep soil layers. In the other years, the general trend was almost identical, but the peaks were much lower, and attributed only to the Control-N treatments (Figure 4).

The main hypothesis of the study is that the N concentration in leaves determines their rate of growth. The expected relationships between $N_c$ in

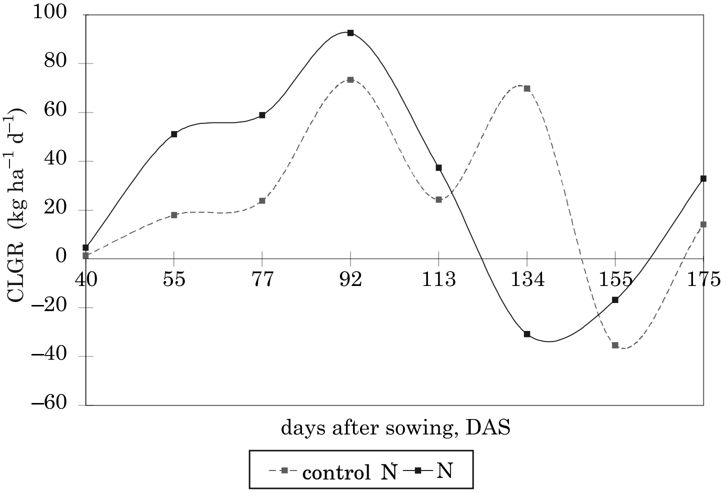

Fig. 2. Dynamics of the growth of dry matter in leaves against the background of nutrient system management, averaged over 2002 and 2003 seasons

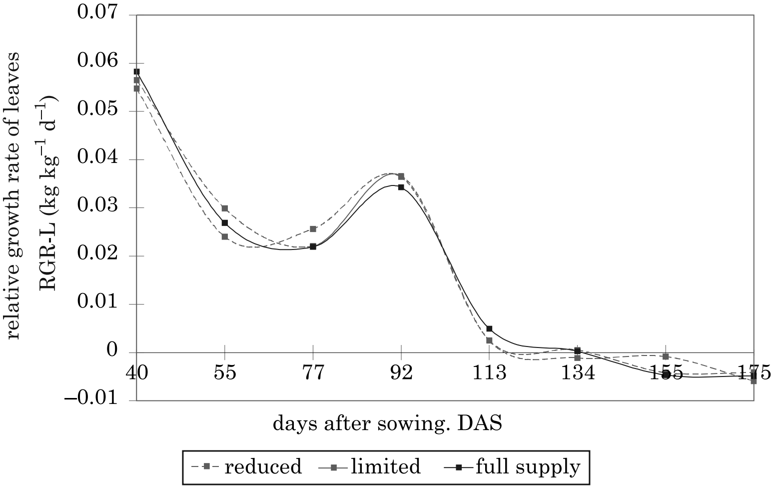

Fig. 3. The relative rate of dry matter growth in leaves against the background of nutrient system management, 2001

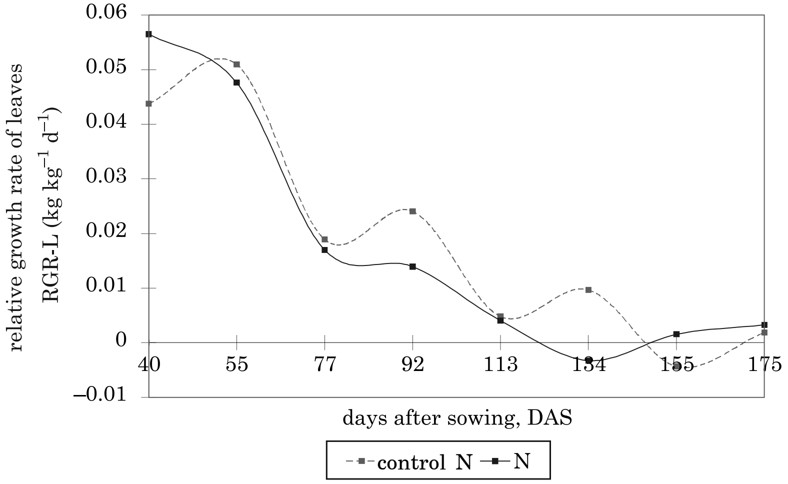

Fig. 4. The relative rate of dry matter growth in leaves against the background of nutrient system management, averaged over 2002 and 2003 seasons

leaves throughout the sugar beet growing season were revealed only for the RGR parameters. Despite the plotted trends of N concentrations during the the growing season (see Table 1), the calculated relationships were subordinated to dry matter trends:

1) 2001:
   a) reduced: $RGR = 0.018N_c - 0.032$ for $n = 8$, $R^2 = 0.\ 70$ and $P = 0.01$;
   b) limited: $RGR = 0.020N_c - 0.041$ for $n = 8$, $R^2 = 0.73$ and $P = 0.01$;
   c) full supply: $RGR = 0.019N_c - 0.039$ for $n = 8$, $R^2 = 0.74$ and $P = 0.001$.
2) 2002+2003:
   a) control-N: $RGR = 0.041N_c - 0.088$ for $n = 8$, $R^2 = 0.88$ and $P = 0.001$;
   b) N: $RGR = 0.035N_c - 0.090$ for $n = 8$, $R^2 = 0.89$ and $P = 0.001$.

As the above equations show, in 2001 the rate of dry matter increase per unit of nitrogen was twice as low as compared in the other years. However, at harvest, dry matter yield of leaves was different only because of the N supply. Therefore, much higher dry matter yield growth per unit N concentration, as found in 2002 and 2003, can be considered as an indicator of the growth rate compensation. This does not agree with the thesis formulated by Boiffin et al. (1992), who underlined the effect of the sugar beet growth rate in the early stages of development on its capability to accumulate dry matter in subsequent stages. In the light of the present study, it can be said that sugar beet plants are able to compensate their rate of growth during the growing season.

## Patterns of dry matter accumulation in storage roots

Accumulation of dry matter in storage roots during the growing season, except the earliest stages, showed significant dependence on the fertilizing treatments, i.e. groups of variants (Table 3). However, it showed high year-to-year variability, in turn modifying the effect of the tested fertilizing variants during most of the growing season. Generally, a trend of dry matter accumulation, irrespectively of the treatment, was progressive during the growing season, but year-specific. Therefore, patterns of dry matter dynamics of the storage root as described by the growth analysis were elaborated separately for 2001 and for the other two years. The absolute taproot growth rate of in 2001, despite some resemblances, was treatment-specific (Figure 5). Dry matter yield of taproots increased, irrespective of the fertilizing treatment, up to 92 DAS, when it peaked and then rapidly declined. At this particular stage of the beet growth, the order of fertilizing groups was as follows:

Table 3

Statistical evaluation of main factors affecting dry matter accumulation in sugar beet storage root during the growing season (Mg ha$^{-1}$ d.m.)

| Factors | Level of factor | Days after sowing, DAS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 40 | 57 | 77 | 92 | 113 | 134 | 155 | 175 |
| Experimental variants (V) | control | 0.004 | 0.094 | 0.642 | 2.394 | 5.350 | 7.003 | 8.94 | 14.26 |
| | PK | 0.007 | 0.175 | 1.034 | 2.985 | 5.290 | 8.944 | 11.83 | 15.20 |
| | KN | 0.19 | 0.339 | 1.458 | 4.668 | 7.837 | 9.792 | 13.91 | 14.68 |
| | PN | 0.018 | 0.222 | 1.450 | 3.800 | 7.432 | 9.912 | 13.84 | 13.37 |
| | W25 | 0.019 | 0.345 | 1.668 | 4.413 | 8.238 | 9.815 | 14.82 | 17.39 |
| | W50 | 0.030 | 0.339 | 1.482 | 4.913 | 8.273 | 10.43 | 14.02 | 18.19 |
| | W100 | 0.021 | 0.337 | 1.371 | 4.508 | 9.190 | 11.17 | 14.35 | 17.62 |
| | W100P | 0.021 | 0.348 | 1.787 | 4.971 | 7.258 | 14.00 | 13.86 | 18.38 |
| LSD$_{0.05}$ | 0.077 | 0.010 | 0.070 | 0.376 | 0.370 | 0.665 | 0.705 | 0.860 | 0.920 |
| Years (Y) | 2001 | 0.019 | 0.406 | 1.252 | 5.380 | 8.038 | 10.09 | 14.65 | 19.92 |
| | 2002 | 0.020 | 0.142 | 2.155 | 3.413 | 6.766 | 10.05 | 12.33 | 14.11 |
| | 2003 | 0.012 | 0.277 | 0.679 | 3.451 | 7.271 | 8.843 | 12.61 | 14.51 |
| F-factor for years | | n.s. | n.s | * | *** | *** | *** | *** | * |
| F-factor for years and variants | | n.s. | n.s. | * | *** | *** | *** | *** | n.s. |

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

reduced < full supply < limited.

In the second part of the season, the rate of growth was highly variable, showing treatment-specific recovery. For the Reduced group, it was detectable in the first decade of September, followed by a subsequent decline.

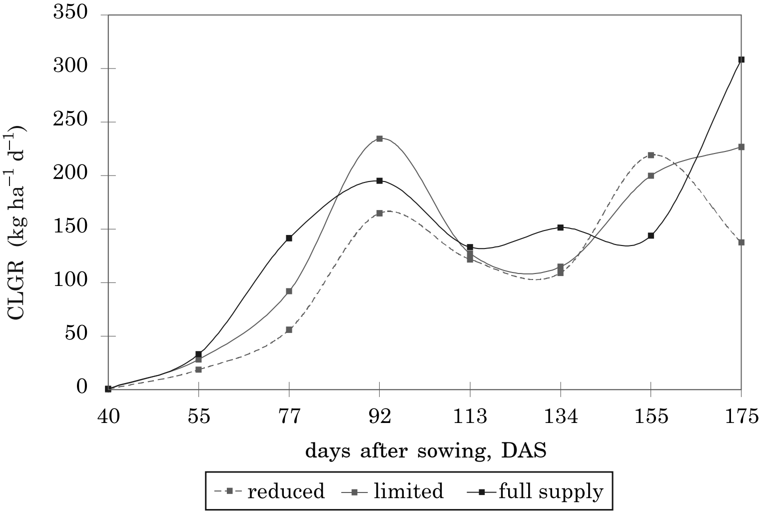

Fig. 5. Dynamics of the growth of dry matter in storage root growth against the background of nutrient system management, 2001 season

For the Limited group of variants, the secondary increase started at the same time as reported for the Reduced variants, but it progressed up to the end of vegetation. A completely different growth pattern was noted to the FS set of variants. In this case, the rate of storage dry matter yield growth was much higher during most of August than for the other treatments. The secondary growth recovery, higher than the first growth, occurred at the end of the growing season. The resulting patterns can be explained by both N the soil resource of nitrogen and its availability as guaranteed by an adequate supply of P and K. The model of the storage root growth as described for the FS group of variants, implicitly corroborate the importance of the growing season duration as the key factor responsible for attaining the sugar beet yield potential (Kenter et al. 2006).

The above hypothesis is fully confirmed by regression models developed for the other two years (Figure 6). As in 2001, the dry matter yield of taproots increased exponentially up to 92 DAS. At that particular sugar beet growth stage, the storage root reached the highest rate of absolute growth, albeit limited by the nitrogen supply. For plants fertilized with nitrogen, it was 200 kg ha$^{-1}$ d$^{-1}$, whereas for the Control-N group, it reached 120 kg ha$^{-1}$ d$^{-1}$. The value for the N group was at the level determined in 2001 for the Limited group of variants. In the second part of the season, its dynamics showed high variability, but went to a decline at the end. Quite a different pattern was observed for the Control-N variant, where the top rate of growth was noted on 134 DAS, preceding a decline and a subsequent increase.

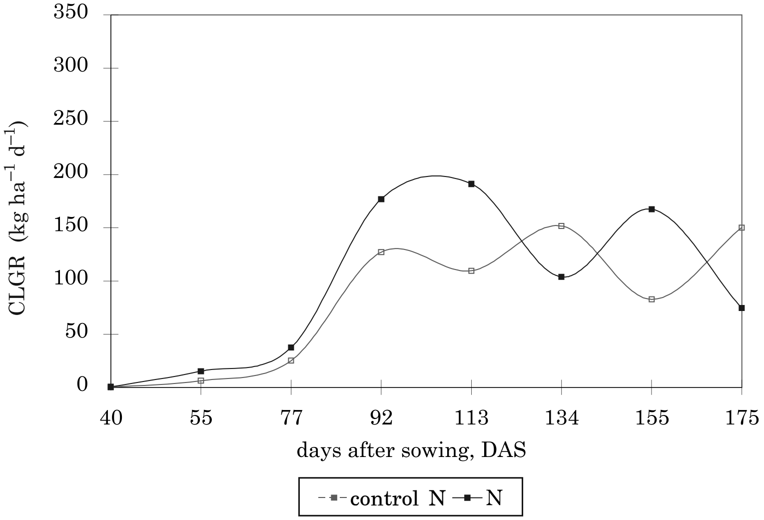

Fig. 6. Dynamics of the growth of dry matter in storage root growth against the background of nutrient system management, averaged over 2002 and 2003 seasons

The relative rate of growth, as the second indicator of the storage roots unit growth, despite significant effects of all the factors, showed strong resemblance among the treatments throughout the growing season (Figures 7 and 8). In both groups of years, two stages of growth are important. As presented by the developed models, the order of variants at the stage of

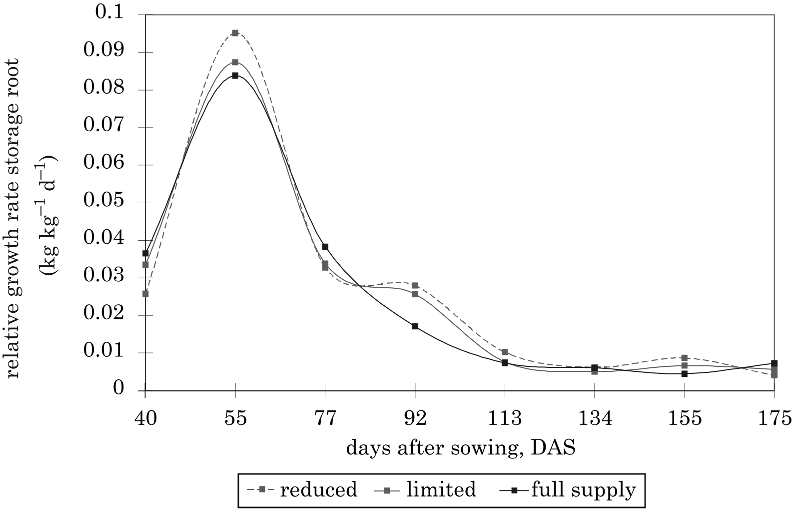

Fig. 7. The relative rate of storage roots dry matter growth against the background of nutrient system management, 2001 season

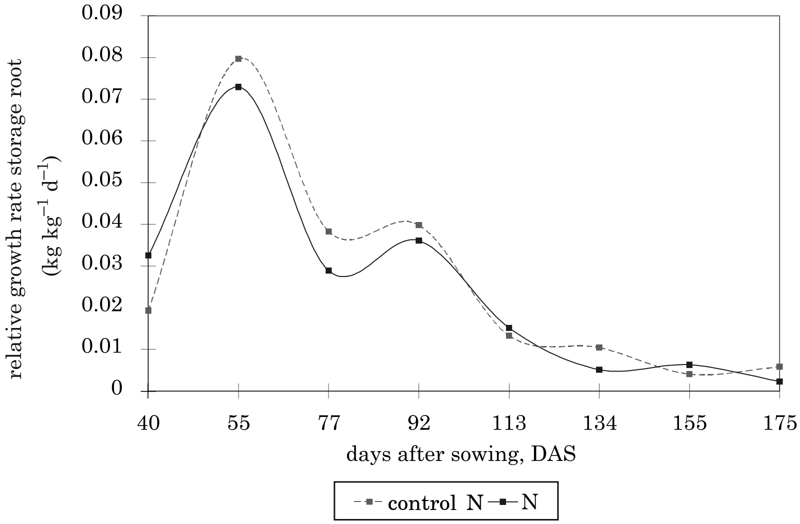

Fig. 8. The relative rate of storage roots dry matter growth against the background of nutrient system management, averaged over 2002 and 2003 seasons

7th leaf (55 DAS) is opposite to the one at the stage of 4th leaf (40 DAS). The observed compensation of the RGR of taproots was much more distinct in 2002 and 2003 than in 2001. However, the level of compensation under conditions of good water supply, i.e. in 2001, was quantitatively much higher.

The expected relationships between N concentration ($N_c$) in taproots throughout the sugar beet growing season were revealed only for the RGR parameter, as presented below:

1) 2001:
   a) reduced: $RGR = 0.012N_c - 0.077$ for $n = 8$, $R^2 = 0.\ 89$ and $P = 0.001$;
   b) limited: $RGR = 0.010N_c - 0.073$ for $n = 8$, $R^2 = 0.86$ and $P = 0.001$;
   c) full supply: $RGR = 0.012N_c - 0.086$ for $n = 8$, $R^2 = 0.89$ and $P = 0.001$.
3) 2002+2003:
   a) control-N: $RGR = 0.010N_c - 0.056$ for $n = 8$, $R^2 = 0.92$ and $P = 0.001$;
   b) N: $RGR = 0.007N_c - 0.051$ for $n = 8$, $R^2 = 0.89$ and $P = 0.001$.

The developed equations clearly indicate higher productivity of a unit concentrated nitrogen in 2001 than in the other years. The mean values for the groups of variants underline the ability of sugar beet plant to compensate growth of taproots in response to the supply of nitrogen. In the other years, the unit productivity of nitrogen was much lower, in turn indicating some limitation of its supply to growing plants. It can therefore be concluded that the relative growth rate of storage roots reveals high sensitivity to the supply of nitrogen. There the thesis formulated by Boiffin et al. (1992) refers fully to this part of sugar beet crop.

## Nitrogen concentration and fraction of storage root

One of the most important indices of dry matter partitioning in sugar beet crop is the storage root's fraction ($SR_f$). This parameter defines the dry matter fraction located in the storage root. The trends of $SR_f$ can be described by the liner regression model (Figure 9). In 2001, its seasonal progress was highly complicated, achieving a linear trend only in the second part of the season, from 92 DAS onwards. The linear course of the trend can be considered as synchronous dry matter partitioning between leaves and the taproot. For the N group of variants, even in this period, a better fit of the real data was obtained using the quadrate model. This type of a model suggests some limitation of the taproot growth due to a prolonged leaf growth induced by the extra N supply.

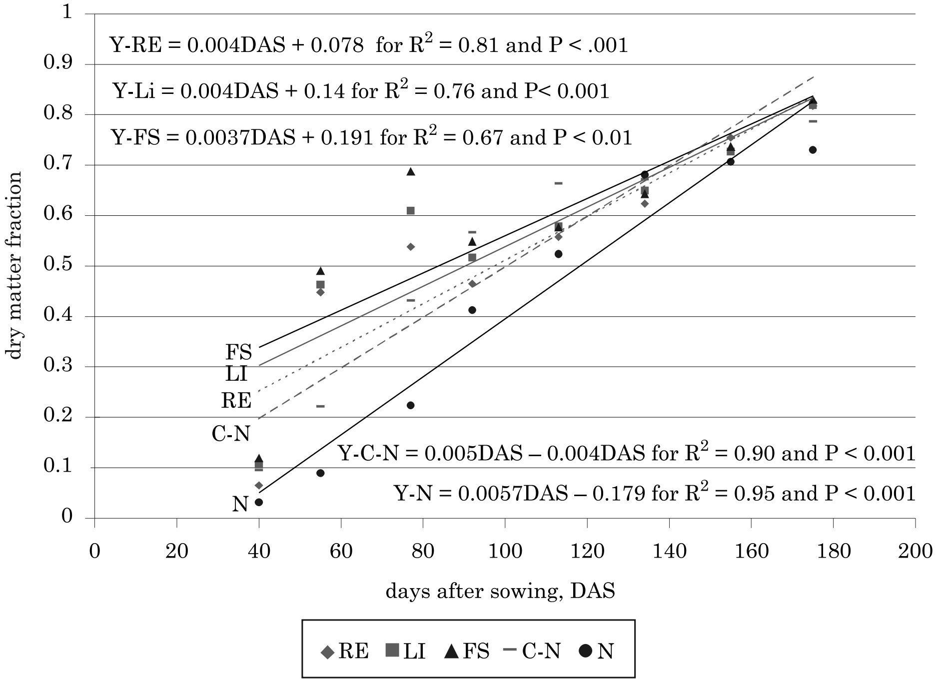

Fig. 9. Trends of storage root fraction in the course of the growing season against the background of nutrient system management

The partitioning of assimilates to leaves and the storage root is strongly influenced by the soil nitrogen dynamics (Werker et al. 1999). Hence, the storage root's fraction index depends on a nitrogen supply to sugar beet plants during the plant growth. Thus, a hypothesis was put forth, suggesting that the N concentration in both plant organs significantly affects the $SR_f$ index. The developed equations based on the means for the distinguished groups of fertilizing variants are as follows:

1) 2001:
   a) reduced:
      i. leaves: $SR_f = -0.082N_{cL}^3 + 0.761N_{cL}^2 - 2.397N_{cL} + 3.076$ for $R^2 = 0.82$;
      ii. taproots: $SR_f = -0.349N_{cTR} + 0.908$ for $R^2 = 0.89$;
   b) limited:
      i. leaves: $SR_f = -0.256N_{cL}^3 + 2.502N_{cL}^2 - 8.029N_{cL} + 8.996$ or $R^2 = 0.94$;
      ii. taproots: $SR_f = -0.356N_{cTR} + 0.962$ for $R^2 = 0.93$;
   c) Full supply:
      i. leaves: $SR_f = -0.280N_{cL}^3 + 2.715N_{cL}^2 - 8.533N_{cL} + 9.305$ for $R^2 = 0.99$;
      ii. taproots: $SR_f = -0.366N_{cTR} + 0.989$ for $R^2 = 0.89$;
2) 2002 + 2003:
   a) control N
      i. leaves: $SR_f = -0.527N_{cL} + 1.898$ for $R^2 = 0.92$;
      ii. taproots: $SR_f = -0.699N_{cL} + 1.149$ for $R^2 = 0.97$;
   b) N
      i. leaves: $SR_f = -0.430N_{cL} + 1.741$ for $R^2 = 0.85$;
      ii. taproots: $SR_f = -0.683N_{cL} + 1.188$ for $R^2 = 0.91$.

The presented sets of equations implicitly allow us to make a simple evaluation of the weather impact during the growing season on the sugar beet growth. In 2001, characterized by an ample water supply during the critical plant growth stages, the weather effect of N concentration in leaves was highly complicated. As shown in Figure 10, this relationship shows a lag-decline phase, characterized by a decline in the of storage root fraction with respect to N concentration, termed as a transition point. The duration of

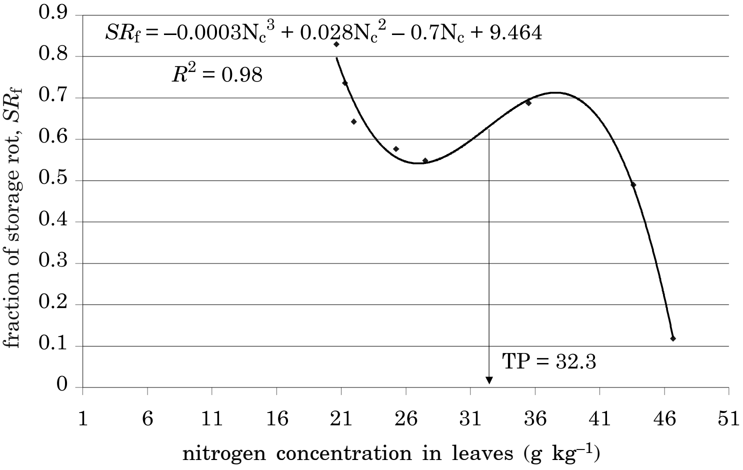

Fig. 10. Fraction of storage root as a function of nitrogen concentration in leaves, the full supply variant, 2001, TP – transition point

the phase and the position of the transition point were variant-specific, with the latter being the low for the FS (TP – 32.3 g N kg$^{-1}$), slightly higher for the Limited (TP – 32.6 g N kg$^{-1}$) and the lowest for the Reduced (TP – 30.9 g N kg$^{-1}$) group of fertilizing variants. Its occurrence can be explained by an extra N supply both from soil resources and the applied N fertilizers, which accelerated the rate of leaf growth. Nitrogen taken up by beet plants prolongs the period of foliage-dominated growth, but without negative impact on the storage root growth. This conclusion is supported by the linear dependence of the storage root fraction on the nitrogen concentration in this beet organ (Figure 9). This pattern of $SR_f$ dependence on nitrogen concentration in leaves was successful, as corroborated by much higher yields of storage roots and sugar in 2001 as compared to the other years. In 2002 and 2003, the $SR_f$ depended linearly on the N concentration in both leaves and storage roots. Therefore, the compensatory pattern of the growth sugar beet organs can be considered as a model, which ensures that sugar beet attains its full yielding potential. However, it is only possible under an ample supply of both water and nutrients. Under water shortage, sugar beet plants are not able to convert the accumulated nitrogen, as indicated by its much higher content in both leaves and storage roots, in productive biomass, observed in 2002 and 2003.

## CONCLUSIONS

1. Nitrogen concentration in sugar beet organs declined during the growing season, according to a linear-plateau regression model in leaves but exponentially in storage roots.

2. The absolute rates of leaf and storage root growth peaked in the mid-season, from 92 and 113 day after sowing; the effect of the year was stronger on leaves than on roots, which responded significantly to a nutrient supply.

3. Nitrogen concentration in both organs of sugar beet significantly affected dry matter growth of leaves and the taproot.

4. Sugar beet plants can compensate their rate of growth; compensation is more efficient in years favorable to sugar beet growth.

5. Dry matter partitioning to the storage root is significantly related to nitrogen concentration in both leaves and the target plant organ; the linear dependence is typical for the storage root, underlying its internal conservatism.

6. The full realization of sugar yield production potential depends on the relationships between N concentration in leaves and the storage root; when these relationships follow a linear regression models, it is indicative of some type of limitation to the crop growth during the growing season.

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