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Potassium fertilization, water shortages during vegetation and crop yielding variability the case of sugar beets

The first part of this review documents the mechanisms of plant resistance to water shortages during growth. It has been indicated, that appropriate supply of crop plants with potassium improves their water management and consequently results in higher resistance to stresses, including droughts. The anti-stress potassium action is a consequence of higher K^+ ions concentration in the soil solution (due to natural fertility or K fertilization); greater perpendicular range of the root system; faster growth rate of above-ground parts of a plant and, consequently, earlier coverage of soil surface. In the second part an attempt was made to explain the major reasons of considerable sugar beet yield losses in Poland, as well as their considerable dependence on weather conditions, i.e. year to year variability. The importance of factors was as follows (i) low, natural, level of available potassium (ii) high frequency of periods with water deficiency and (iii) insufficient, in relation to the nutrient requirement, K fertilization. Using experimental data it was shown that appropriate nutrition of sugar beet plants with potassium allowed them to survive during the critical growth stages and, consequently, reduced the risk of yield losses caused by drought.

Key words: crop plants, plant resistance to stresses, potassium functions, sugar beets, water shortages, yield losses

Pierwsza część opracowania przedstawia mechanizmy odporności roślin na niedobory wody w okresie wzrostu. Wskazano na znaczenie zaopatrzenia roślin uprawnych w potas, jako sposób poprawy gospodarki wodnej i w konsekwencji zwiększenia odporności na stresy, w tym na niedobory wody. Antystresowa rola potasu wynika ze zwiększonej koncentracji jonów K^+ w roztworze glebowym (skutek naturalnej zasobności w potas lub jako efekt nawożenia potasem); większego pionowego zasięgu systemu korzeniowego; większej szybkości wzrostu organów nadziemnych rośliny i w rezultacie wcześniejszego zakrycia powierzchni gleby. W drugiej części opracowania podjęto próbę wyjaśnienia głównych przyczyn osiągania przez polskich rolników słabych plonów buraków cukrowych, jak również ich znacznej zależności od przebiegu pogody. Gradacja czynników jest następująca: (i) niski, naturalny poziom zasobności gleb w potas; (ii) duża częstotliwość susz w okresie wegetacji roślin uprawnych; (iii) niedostateczne, z punktu widzenia potrzeb nawozowych uprawianych roślin, nawożenie potasem. Używając danych doświadczalnych wykazano, że odpowiednie odżywienie buraka cukrowego potasem pozwala tej roślinie na przetrwanie niekorzystnych warunków wodnych, a tym samym na zmniejszenie ryzyka utraty plonu spowodowanego suszą.

Słowa kluczowe: burak cukrowy, funkcje potasu, niedobory wody, odporność na stres, rośliny uprawne, straty plonu

INTRODUCTION

Crop yields are influenced by the temperature, radiation and CO_2 supply. Water and nutrients' supply are the factors limiting plant growth and yielding. In practice, crop growth and productivity are limited by three major factors such as drought, extreme temperatures, and soil nutrients' depletion (Rabbinge, 1993).

In many areas of the World, the occurrence of drought is a fact of nature. Consequently, crop production decreased in those regions where the climatic anomalies or disasters have become more frequent. In humid areas of the World, including Poland, crops are also subjected to variable and unpredictable periods of droughts of different duration (Koźmiński, et al., 1990; Farat et al., 1995; Plenzler, 1995).

Efficient allocation of agricultural means and farmers' efforts to improve the agricultural production and to prevent land degradation require insight in the processes responsible for efficient water use. One of these processes is the depletion of soil nutrient reserves. Declining soil fertility is usually described in terms of considerable yields' variability from year to year, as a logical consequence of current agricultural practice (Walker, 1994).

The objective of this review is twofold. The first one is to document the mechanisms and factors responsible for plant resistance to water deficits. The second is to illustrate that adequate potassium management could be used as the main tool to ameliorate the negative effects of water shortages over the growing season on growth and yields of sugar beet in Poland.

I. THEORETICAL CONSIDERATIONS — MECHANISMS OF PLANT ADAPTATION TO WATER SHORTAGES

Transpiration and crop water needs

All biophysical and physiological processes occur in an aqueous medium and at defined ranges of temperature, which must be kept constant. Therefore, most of the water taken up by a plant, i.e. about 90% is used for plant cooling. Water, exactly water vapor, evaporates into air through leaf openings, called stomata. The mechanism of transpiration is controlled by the plant's own biological clock (circadian rhythm), that shows diurnal patterns of activity. Normally, stomata open when the light strikes the leaf in the morning and close during the night. The mechanisms of these processes depend on K^+ ions availability.

Crop water use (evapotranspiration — ET) is defined as the amount of water used by a crop for growth and cooling. The classical (physiological) approach to plant water needs (transpiration coefficient or water requirement) refers to the number of water units by weight transpired per unit of dry matter accumulated in a given time interval (Lomas, 1995).

In agricultural practice, in order to describe the plant water needs, two other terms are frequently used (Doorenbos and Pruitt, 1977):

— rainfall water needs are defined as the amount of natural rainfalls in the period from sowing to harvesting; optimally distributed within the growing season and satisfactory for good yield,
— water shortages are defined as the difference between rainfall water needs and the amount of precipitation within the growing season.

Plant resistance to shortages of water

Crop water use depends on several factors, of which three are highly significant:
— crops sensitivity to water stress at given stage of growth (Table 1);
— actual soil water content;
— the pattern of weather courses.

Plant extracts the water from the zone used by the root system. The spatial pattern of water uptake from various regions of the soil depends on root distribution as well as the distribution of moisture content within the soil profile. Water is removed from deeper layers as root penetration increases and water remaining near the surface is held at more negative matrix potential. Water uptake and extraction patterns are related to root density (Taylor and Klepper, 1978; Brown and Biscoe, 1985).

Table 1

Critical growth stages of the main crops to water stress
Krytyczne fazy rozwoju głównych roślin uprawnych ze względu na stres wodny
(Doorenbos and Pruitt, 1977)

Crop Roślina uprawna	Critical growth stages Krytyczne fazy rozwoju	Symptoms of water stress Symptomy stresu wodnego
Cereals Zboża	During shooting, heading, anthesis, and early ripening stages; Podczas strzelania w źdźbło, kłoszenia, kwitnienia i we wczesnych fazach dojrzewania	Dark green colour, then burning of lower leaves; Ciemnozielona barwa, przypalenie dolnych liści
Maize Kukurydza	Two weeks before tasseling through silk stage and until kernels become firm Dwa tygodnie przed rozwinięciem wiechy, poprzez kwitnienie, aż do fazy wypełniania ziarniaków	Curling of leaves before midday, dark-green colour of leaves Zwijanie się liści przed południem, ciemnozielony kolor liści
Potato Ziemniak	Flowering and tuber formation to harvest Do kwitnienia i formowania bulw aż do zbioru	Leaves wilting during hot days Więdnięcie liści podczas upalnych dni
Sugar beet Burak cukrowy	Secondary expansion of the storage root Przyrost wtórny korzenia	Leaves wilting during hot days Więdnięcie liści podczas upalnych dni

The maximum rate of water use by a plant occurs at field capacity, i.e. at maximum available water content in soil. As the soil dries, the its available water content decreases, so leading to a decrease in plant water potential, what does not depend solely on the soil water potential but also on plant structure and transpiration rate. The prolonged drought disturbs plant diurnal activity. Stomata tend to lose their control of water loss from the leaves, further increasing the stress. The photosynthesis rate declines and respiration tends to increase and, consequently, dry matter accumulation is reduced. Consequently, decreases amounts of produced sugars, which affect many physiological processes responsible for growth of new tissues, including roots. Shortage of assimilates at the roots decreases the rate of their growth and, as a consequence, root system may be less able to utilize reserves of water stored in deeper soil layers (Taylor and Klepper, 1978; Day 1981; Huck, 1984; Smucker, Aiken, 1992).

The main scientific problem, is the question how water deficit may be ameliorated. In agricultural practice, irrigation and breeding used to be treated as the main ways to overcome water shortages. The basic solution is to supply more water, i.e. to irrigate. But not all farmers are in position to invest in irrigation equipment. The second solution is to find plant species, or even varieties, well adapted to water stress conditions. So far, these efforts are not successful (Monneveux, Belhassesn, 1996; Almani et al., 1997; Mossoud et al., 1998).

The third solution directly refers to plant physiological processes, which are better maintained under stress conditions if adequate supplies of nutrients are available throughout the growing season. Deficit of the nutrients reduces physiological functions of the plant, making energy transfer and other growth processes less efficient (Day, 1981; Bergmann, 1992; Amstrong, 1998).

II. POTASSIUM AS WATER-STRESS AMELIORATIVE NUTRIENT

Potassium uptake by plant

Plants absorb potassium as K^+ ions. Its availability and plant uptake are affected by several factors such as soil moisture content, soil aeration and oxygen level, soil temperature, cation exchange complex, rooting depth.

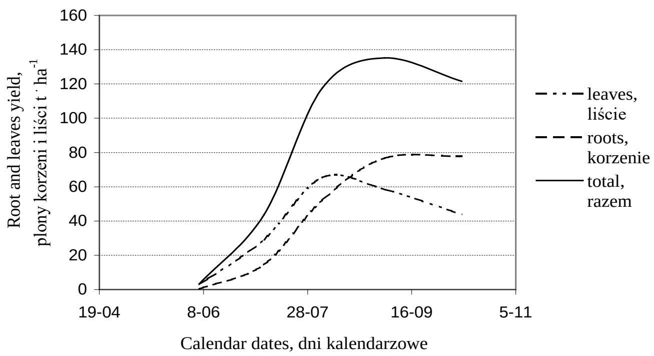

Fig. 1. Growth dynamics of sugar beet
Rys. 1. Dynamika wzrostu buraków cukrowych

There is good evidence that higher soil moisture content usually means greater availability of potassium. Increasing soil moisture content results in increased diffusion of K^+ ions to plant roots and their greater availability. Hence, adequate supplies of N, P, and especially K ions, must be readily available to cover the crop plant requirements and keep it healthy and vigorously growing over the whole growing season (Fig. 1).Therefore, the crop response to K fertilization is stronger in dry years than in the wet years (Grimme, 1991).

Potassium and plant stress resistance

Plenty of research documents that the drought less affects the crop yielding when K is readily available throughout the growing season. This is in part due to, its influence on:

— earlier and deeper root growth, potassium increases the size and depth of a crop roots and makes the root system more intensive, so the plants can obtain more nutrients and water over larger occupied soil area; extensive root system gives the plant a larger capacity for storing sugars, water, and soluble proteins;

— faster regrowth of stressed root system, this feature is especially important to forage and to winter crops. In spring, the rate of growth of both crop groups is very high. Their nutritional needs, especially for nitrogen, are also very high. High potassium availability and K plant content are prerequisites for the achievement of satisfactory yields;

— faster closing the canopy, when the crop canopy closes, the ratio of transpiration to evaporation increases, what means more of the available water used by the crop;

— efficient use of available water throughout the main season, the deeper root system stays in contact with moist soil for a longer time during drought (Huck, 1984; De Nobili et al., 1990; Grzebisz , 1990; Amstrong, 1998).

The pattern of potassium uptake by sugar beets

The high-yielding crop plants need large quantities of potassium, and take potassium in amounts as high or even higher than the nitrogen. The Figure 2. shows the relative dynamics of potassium uptake by sugar beet plants.

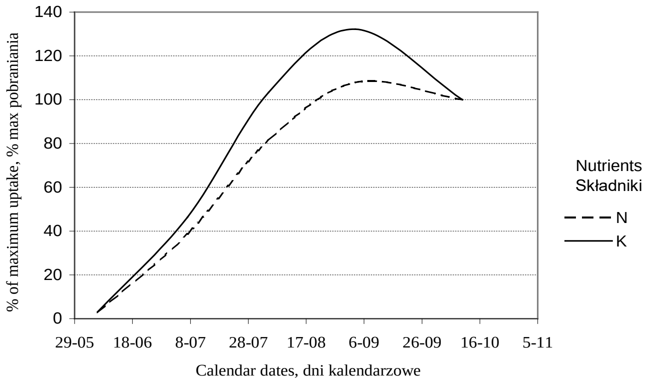

Fig. 2. Dynamics of N and K uptake by sugar beets
Rys. 2. Dynamika pobierania N i K przez buraki cukrowe

The highest uptake rate of nitrogen and potassium was observed in July (the steepest part of the K uptake line) and, amounted on average to 8.5 kg K·ha^{-1}·day^{-1} (Grzebisz et al., 1998). The highest K uptake may reach up to 15 kg K·ha^{-1}·day^{-1} (Draycott, 1996). These high amounts of potassium cannot be supplied by means of foliar application, i.e. through the leaves. They must be present in available forms in the soil solution, what largely depends on water regime and plant root system activity (Grzebisz, 1990).

It could be concluded that particularly the K-demand of high-yielding crops is often underestimated and critical growth stages are not always well recognized (Table 2). As a result, the efficiency of applied nitrogen fertilizers, due to insufficient supply of K, is also often lower that expected. This specific phenomenon was explained by Marschner et al. (1996). Lack of potassium restricts the nitrate transport, what leads to nitrate reduction in the roots and accumulation of amino acids. Accumulation of these compounds in roots at adequate K and excessive N may send a signal, via a feed-back effect, to the root to restrict N uptake, what, in turn, lowers the N fertilizer efficiency. This also means that the plant is not able to take more N if K is in short supply (Fig. 3).

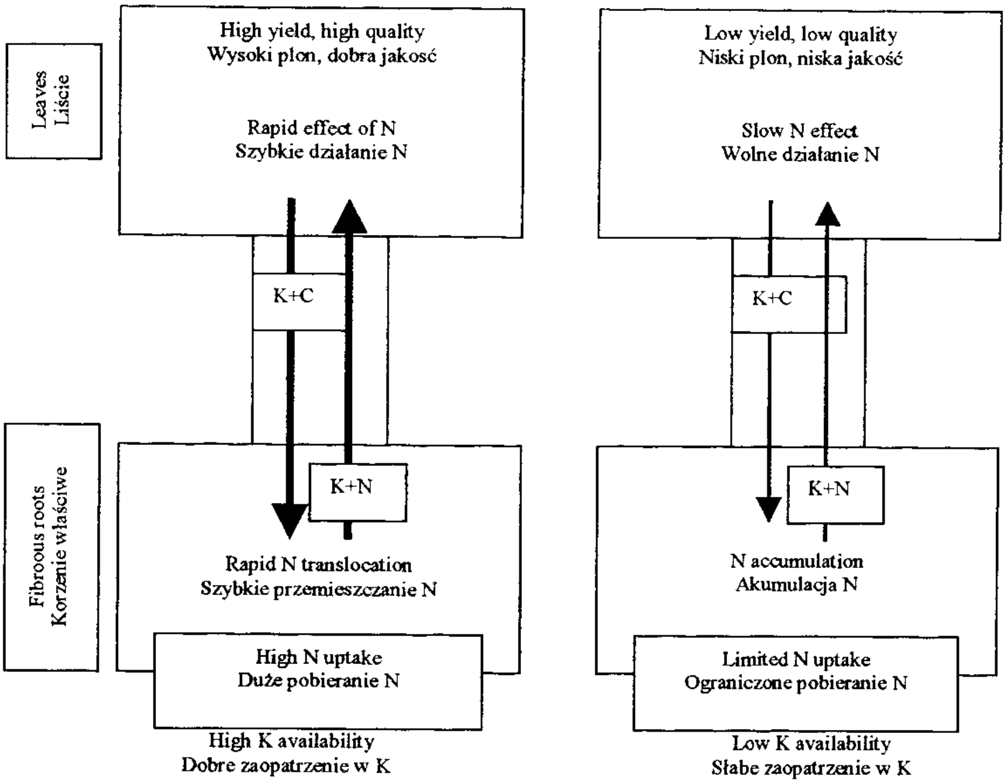

Fig. 3. Plant response to nitrogen and potassium nutrition (Marschner et al., 1996, modification)
Rys. 3. Reakcja rośliny na odżywienie azotem i potasem (Marschner i in., 1996, modyfikacja)

Table 2

Critical growth stages of the main crops related to potassium nutrition(according to different authors)
Krytyczne fazy rozwoju głównych roślin uprawnych ze względu na odżywienie potasem (według różnych autorów)

Crop Roślina uprawna	Critical growth stages Krytyczne fazy rozwoju
Cereals Zboża	shooting — anthesis strzelanie w źdźbło — kwitnienie
Oil-seed rape Rzepak	rosette— anthesis faza rozety — kwitnienie
Sugar beet Burak cukrowy	secondary extension of the storage root — mid-season (July/August) od początku wtórnego przyrostu korzenia spichrzowego — połowa sezonu (przełom lipca/sierpnia)
Potato Ziemniak	anthesis — tubering — tubers growth kwitnienie — zawiązywanie bulw — wzrost bulw
Maize Kukurydza	from the fifth leaf up to tasseling od piątego liścia do kwitnienia

III. NATURAL AND AGROTECHNICAL LIMITATIONS FOR SUGAR BEETS GROWTH IN POLAND

Climate and droughts in Poland

Poland is located at the extensive European Plain. Western air circulation predominates in this area, strongly affecting the weather course. With respect to agriculture, the most substantial problem is water. The entire area of Poland, except for the mountains, is characterized by the annual precipitation between 500 to 600 mm. The lowest total occurs in the central — western part of Poland, higher in the Pomeranian region and in the belt of elevation (Plenzler, 1995).

As a general rule, the climatic conditions in Poland are not very favorable for cultivated plants because of the frequent deficits of precipitation during the vegetative season. In years 1951–1990, short lasting droughts comprised 20% of vegetative seasons. Almost all droughts occurred in spring/early summer periods. Droughts occurred most frequently in Wielkopolska, Mazowsze, Dolny Śląsk and Podlasie regions. In addition, shortages of rainfall occur in combination with high temperatures leading to increased evapotranspiration. These two factors and prevailing light soils bring about some negative effects in agriculture production. The deficit of precipitation is an essential factor that restricts agricultural production and decreases yields by up to 30–40% (Farat et al., 1995; Plenzler, 1995).

Fertilizer consumption and potassium resources in soils

With respect to fertilizer consumption in Poland, the most important current trends are as follows:

— decreasing amount of mineral fertilizers applied per ha of arable land,
— decreasing amount of organic fertilizers produced by a farm.

These two processes are extremely dangerous for stability of crop production in Poland, because of decreasing soil fertility, particularly concerning available phosphorus and potassium. During the period 1989–2000 the amounts of applied NPK fertilizers decreased by more than 50%. In 1989, about 0.26 kg P and 0.65 kg K were applied per 1 kg N. Nine years later this relationships were 1 to 0.35 and 1 to 0.41, respectively (Polish yearbooks of agriculture, 1991–2000).

Potassium deficient soils tend to be light to medium textured and imperfectly to poorly drained in their natural state. For these soils, recommended rates of potassium fertilizer should be greater than the expected crop removal rates. This is the main way to gradual building up of available soil potassium. However, decades of cropping without sufficient replacement of the K removed with harvested plant portions have depleted soil K resources to yield-limiting levels in some areas of Poland. A recent survey of 2910 samples (1993–1998) shows that many polish soils urgently need K fertilizer supply. The data presented by Agrochemical Stations reveal also that only 24 percent of soils still test very high in K. The widely published figures referring to major nutrients balance indicate a large deficit of potassium, phosphorus and magnesium. The highest K imbalance occurs in the central-eastern part of the country, where more than 50 percent of samples tested may be at yield limiting levels. On most areas where oil-seed rape is grown the soils are poor in K, what ranges from 30% to above 50% (Fotyma, Gosek, 2000).

IV. SHORT-TERM MANIFESTATIONS OF CROP RESPONSE TO K FERTILIZATION

The case study — sugar beets

To elucidate the effect of water and K availability on crop yield, an exhaustion-type field experiment was established in 1991 at the Brody Research Station (Agricultural University of Poznań, Poland) on very K-fertile loamy sand developed on the underlying sandy loam. In years 1998–1999, sugar beet, cv. Mieszko was grown as a test crop.

Table 3

Effect of water and potassium supply on root yields of sugar beets
Wpływ zaopatrzenia w wodę i potas na plony korzeni buraka cukrowego

Treatments: K fertilization (A) irrigation (B) Czynniki: nawożenie potasem (A) i nawadnianie (B)	Yield Plon ($t \cdot ha^{-1}$)	Relative yields Plony względne (%)	Relative gains/losses Względne zyski/straty (%)
K fertilized — Nawożone K			
Irrigated — I — Nawadniane — I	62.3	124	+ 24
Drought — D_1 — Susza — D_1	43.8	87	- 13
Drought —- D_2 — Susza — D_2	37.2	74	- 26
Control — C Kontrola — C	50.3	100	0
K non-fertilized — Nie nawożone K			
Irrigated — I — Nawadniane – I	49.2	98	- 2
Drought — D_1 — Susza — D_1	34.1	68	- 32
Drought — D_2 — Susza — D_2	33.2	66	- 34
Control — C Kontrola — C	43.0	85	- 15
$LSD_{0.05}$ A × B $NIR_{0,05}$ A × B	5.6	—	—

The experimental design was quite simple comprising two levels of applied K (0, 130 kg $K \cdot ha^{-1}$) and four water treatments, which were control (C — rainfall only), irrigated to 70%

FC (I), and 4-weeks drought periods imposed in July (D_1) and in August (D_2). A static shelter designed to cover the experimental area of 72 m^2 achieved the soil moisture stress at particular stages of sugar beet growth.

As shown in the Table 3, the water and K supply significantly influenced the final yields of roots. With respect to imposed drought, potassium supply significantly affected the final root yield. Thus, plants grown at the K fertilized treatments were only able to decrease partly the negative effect of water stress. However, the extent of yield decrease strongly depended on K fertilization. The lowest response of sugar beet plants to K fertilization was found when the water stress was imposed in August.

The same pattern, as presented for yield of roots was found for the final yield of recoverable sugar. The main reason is the almost insignificant effect of experimental factors on quality parameters of the beet roots (Table 4).

Table. 4

Quality characteristics of sugar beet roots
Charakterystyka jakościowa korzeni buraków cukrowych

Factors Czynniki	Level of factors Poziom czynników	Sugar content Zawartość cukru %	Melassogenic substances Związki melasotwórcze Mm/100g N α-amin	K	Na	Sugar losses Straty cukru %	Technological sugar content Wydatek %
Potassium	+	16.34	1.27	5.20	0.49	2.05	14.29
Potas	—	16.36	1.28	4.59	0.48	1.98	14.38
NIR $_{0,05}$ LSD $_{0.05}$		—	—	0.44	—	—	—
Water* treatment Warianty wodne	C	16.45	1.29	4.81	0.53	2.01	14.26
	I	16.28	1.30	5.09	0.49	2.05	14.40
	D_1	16.29	1.25	4.91	0.46	2.01	14.28
	D_2	16.38	1.26	4.77	0.46	2.00	14.38
NIR $_{0,05}$ LSD $_{0.05}$		—	—	—	—	—	—

* See text for details

V. YEAR TO YEAR VARIABILITY OF CROP YIELDS

An assessment of the main factors affecting sugar production (y) in Poland within 1961–1997 indicates that the year to year variability in root yield was the main factor responsible for 34% of variability in sugar yield (Grzebisz, 2000):

$$Y = 0.494 + 0.039 x_1 \qquad R^2 = 34\% \qquad (1)$$

where:

x_1 — yield of sugar beet roots

Harvested yields of the major cash crops such as winter wheat, sugar beets and oil-seed rape are low (Table 5). In 1990, characterized by a relatively high consumption of fertilizers, the best actual yields of the major crops reached only 60% their potential productivity. Ten years later farmers were able to exploited about 50% yielding potential of cultivated crops.

In order to explain this phenomenon the Authors used the real data from Figures 1 and 2. The obtained regression model of sugar beet matter accumulation (SB_{DM}) over the growing season (Grzebisz et al., 1998) shows its significant dependency on potassium uptake (K_{up}).

$$SB_{DM} = 0.257\ K_{up} - 0.8; \qquad R^2 = 0.97 \qquad (2)$$

Using this equation, one may calculate the K requirements for given yield or *vice versa*. For example, the average yield of sugar beets amounting to 38 $t \cdot ha^{-1}$ of storage roots (+30.5 $t \cdot ha^{-1}$ of tops — the average yield in 1990) removes from the field 270 kg $K \cdot ha^{-1}$. But, the K removal for the potential yield of roots (according to the COBORU (1991, 2000) reference data — see Table 5) amounting 63 $t \cdot ha^{-1}$ of storage roots (+50.4 $t \cdot ha^{-1}$ of tops) would reach 445 kg $K \cdot ha^{-1}$. In other words, the lower potassium uptake, the lower yield of harvested roots could be expected.

Table 5

Potential and actual yields of the main crops in Poland
Potencjalne i rzeczywiste plony głównych roślin uprawnych w Polsce

Crops Rośliny uprawne	1990 Yields Plony			1999 Yields Plony		
	potential* potencjalne*	actual** rzeczywiste**	losses straty	potential* potencjalne*	actual** rzeczywiste**	losses straty
	$t \cdot ha^{-1}$	%		$t \cdot ha^{-1}$	%	
Winter wheat Pszenica ozima	6.86	3.75	55	6.52	3.66	56
Spring barley Jęczmień jary	6.11	3.52	58	5.70	3.00	53
Oil-seed rape Rzepak	4.03	2.41	60	4.06	2.08	51
Sugar beet Burak cukrowy	63.0	38.0	60	67.8	33.8	50

* — Yields of the check variety — COBORU annuals (1991–2000); Plony odmiany wzorcowej — zeszyty COBORU (1991– 2000)
** — Polish Yearbook of Agriculture (1991– 2000); Rocznik Statystyczny (1991–2000)

The second way of calculating the weakest stage of plant crop growth may be done using Fig. 2 and equation (2). The above calculated amounts of potassium taken up by sugar beet grown in 1990 represents only 62% K final uptake of the pattern crop. Non-limiting grown plants achieved this level of K uptake in the first decade of July.

About 150 years ago, a great German scientist Justus von Liebig (1803–1873) stated that: „A deficiency of any single nutrient is enough to limit the yield”. Presently, in Poland this statement should be rewritten as follows „A deficiency of potassium is enough to limit yields of cultivated crops”.

CONCLUSIONS

The need to increase the yield increases crop vulnerability to drought. High frequency of the periods with water deficiency during vegetation season, low natural potassium availability and insufficient — in relation to nutrient requirements — fertilization are among the main reasons why the farmers in Poland harvest poor yields as well as their considerable dependence on weather conditions.

Following recommendations may be useful to the farmers:

1. Best strategy for dealing with an expected drought is the best fertilization strategy for a good year. Adequate nutrition is essential to take advantage of the good growing seasons, but it is also the best management approach to counteract drought.
2. The proper management of soil K is probably one of the best ways to exploit sugar beets production potential and, as a result, to increase N fertilizer efficiency.
3. Potassium is a nutrient, which exerts an uniquely positive influence on water management of crop plants. Therefore, it is important to assess the conditions limiting K uptake by crop plants such as:

— low soil and air temperatures,
— deficit of precipitation in critical stages of plant growth,
— occurrence of compacted soil layers in the rooting zone of a crop plant,
— insufficient fertilization with potassium,
— Unfavorable soil reaction.

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