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EFFECT OF ZINC FOLIAR APPLICATION AT AN EARLY STAGE OF MAIZE GROWTH ON PATTERNS OF NUTRIENTS AND DRY MATTER ACCUMULATION BY THE CANOPY

Part I. Zinc uptake patterns and its redistribution among maize organs

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Abstract

As reported in the paper by Grzebisz et al. (this issue), maize crop treated foliarly with fertilizer zinc at early stages of growth produced significantly high yields. Growth analysis procedures were applied to explain various effects of fertilizer zinc on grain yield increase and zinc accumulation and redistribution among maize organs in the course of the growing season. Therefore, based on the obtained zinc uptake characteristics, two major and one minor, but time-separated *hot spots* of zinc accumulation by maize plants have been distinguished. The first one, as described by RUR-Zn data, extended from the BBCH7 to BBCH9 stages. The second one, as expressed by CUR-Zn data, appeared during the milk stage of kernels growth and could be decisive for kernels sink capacity for accumulating carbohydrates. A minor *hot spot*, which occurred at tasselling may be responsible for pollen production and activity. The first zinc *hot spot* has also revealed the diagnostic problem of soil and plant tests for zinc. Current tests tend to overestimate plant zinc nutritional status, and therefore need to be urgently revised. Vegetative organs such as leaves and stems were only the minor sources of

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zinc for developing maize kernels. During grain filling period, most zinc absorbed by maize plants originated from soil resources.

Keywords: relative uptake rate (RUR), crop uptake rate (CUR), zinc, maize.

Wpływ dolistnego stosowania cynku we wczesnej fazie wzrostu kukurydzy na wzorce akumulacji składników pokarmowych i suchej masy przez łan

Cz. I. Wzorce akumulacji cynku i rozmieszczenie składnika między organami rośliny

Abstrakt

Z pracy wynika, że kukurydza traktowana dolistnie nawozem cynkowym we wczesnej fazie rozwoju wydała większe plony ziarna. Celem wyjaśnienia mechanizmu działania nawozu cynkowego na plony ziarna i na akumulację cynku przez rośliny w okresie wegetacji zastosowano procedury analizy wzrostu. Na podstawie parametrów pobrania cynku, wyznaczono dwie główne i jedną drugorzędną fazę krytyczną akumulacji tego pierwiastka przez kukurydzę. Pierwsza faza, opisana przez RUR-Zn, pojawiła się w okresie od 7. (BBCH 17) do 9. liścia (BBCH 19) i była prawdopodobnie związana z inicjacją zawiązków kwiatowych. Druga, reprezentowana przez CUR-Zn, zaznaczyła się w fazie dojrzałości mlecznej ziarniaków i mogła wpływać na zdolność ziarniaków do akumulacji węglowodanów. Trzecia faza krytyczna, pojawiająca się w fazie wiechowania, wiąże się prawdopodobnie z produkcją i żywotnością pyłku. Pierwsza faza krytyczna ujawniła także problem wiarygodności obecnych testów glebowych i roślinnych dla cynku, które przeszacowują stan odżywienia kukurydzy cynkiem i wymagają pilnej rewizji. Organy wegetatywne, takie jak liście i źdźbła, nie były głównymi źródłami cynku dla rosnących ziarniaków kukurydzy. W fazie nalewania ziarna kukurydza pobierała większość cynku z zasobów glebowych.

Słowa kluczowe: względna szybkość pobierania (RUR), szybkość pobierania przez łan (CUR), cynk, kukurydza.

INTRODUCTION

Zinc is one of the most important micronutrients in the production of many crop plants such as rice, maize and wheat, or soybean, which all are worldwide cultivated. It has been well recognized by scientists that zinc affects many processes governing plant life cycles. Some metabolic processes such as enzymatic activity, auxin synthesis, carbohydrate metabolism, protein synthesis are of crucial importance for plant growth and in turn for efficient control of nitrogen metabolism. There are also many physiological processes such as pathogen pressure, drought or heat, effectively controlled by zinc activity and in turn resulting in higher resistance of cultivating plants to abiotic and biotic stresses (Grusak et al. 1999, Marschner 1986). Soils poor in available zinc are a serious quantitative and qualitative stress factor for crop plants. These soils cover almost 50% of world arable lands, mostly in dry and acid areas of the world (SILLANPAA 1990).

The yield potential of maize is extremely high, but its realization is possible provided that supply of nutrients and efficiency of applied nitrogen are high (MURREL, CHILDS 2000). There are few scientific papers reporting quantitative aspects of zinc fertilizers in maize grain production (FECENKO, LOŻEK 1998; GRZEBISZ et al. (this issue). All these papers stress the importance of zinc applied at early stages of maize growth on its yields, which in turn is related to higher efficiency of fertilizer nitrogen. The found yield increases are directly related to the components of yield structure, mainly the number of kernels per cob in response to zinc application.

A plant growth analysis procedure (HUNT et al. 2002) was applied in order to explain the experimentally corroborated effect of zinc on maize yielding. In this specific case, it was necessary to determine the most crucial stages of zinc accumulation in order to exhibit plant behavior in the course of the growing season.

The main objectives of this study were to describe the patterns of zinc uptake by maize plants in order to point out its effect on grain yield.

MATERIALS AND METHODS

One-factor experiments with four rates of zinc application, i.e., 0.0, 0.5, 1.0 and 1.5 kg Zn ha^{-1} as zinc oxy-sulphate were conducted in 2002 and 2003 growing seasons. The general design and experimental details of this study are presented by GRZEBISZ et al., (this issue). For purposes of this particular study, 8 plants were sampled (equal to 1 m^2) in 10 consecutive stages of maize growth according to the BBCH code: 14 (37 days after sowing – DAS), 17 (48 DAS), 19 (58 DAS), 39 (69 DAS), 59 (79 DAS), 67 (89 DAS), 75 (104 DAS), 83 (118 DAS), 87 (132 DAS), 89 (140 DAS). At each stage of maize growth, the harvested plant sample was partitioned, according to its stage of development, into sub-samples of leaves, stems, cobs, shanks, husks, kernels, and then dried (65°C). The results are expressed on a dry matter (DM) basis.

The growth analysis procedure was applied to determine the Crop Growth Rate (CGR) parameter, which for the purpose of this study is termed Crop Uptake Rate of Zinc (CUR_{Zn}), as reported below (HUNT et al. 2002):

$$CUR = \frac{W_2 - W_1}{T_2 - T_1}\,.$$

The second growth parameter used in the study was the Relative Growth Rate (RGR), termed as Relative Uptake Rate of zinc (RUR_{Zn}). It was calculated for any individual plant using the formula:

$$RUR = \frac{\ln W_2 - \ln W_1}{T_2 - T_1}\,,$$

where:

CUR_{Zn} – crop zinc uptake rate, mg m^{-2} d^{-1};

RUR_{Zn} – plant zinc uptake rate, μg mg^{-1} d^{-1} per maize plant;

W_2, W_1 – yield of dry matter; or nitrogen uptake; or zinc uptake in two consecutive samplings; g, or mg, or μg per m^2, respectively;

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

The experimentally obtained data were subjected to conventional analysis of variance with least significant difference (LSD) values calculated at P = 0.05, and analysis of simple regressions.

RESULTS

Zinc accumulation patterns

Significant effect of zinc applied at early stages of maize growth on its own accumulation by plants was found in 8 out of 10 sampling dates (Figure 1). The general pattern of zinc accumulation, based on a quantitative factor, can be divided into two distinct time-phases. The first one extended from the stage of 7^{th} leaf (BBCH 17) up to full flowering (BBCH 67), when Zn uptake by maize first exceeded 100 g Zn ha^{-1}. The second one extended from full flowering up to final maturity (BBCH 89). The first significant effect of fertilizer zinc was noted at the stage of 7^{th} leaf. However, at this particular stage, the most important reason of enhanced zinc uptake was not the plant's biomass increase but a huge rise of Zn plant concentration (Table 1). Plants grown on the control plots contained about 35 mg Zn kg^{-1} DM, as compared to 87 mg Zn kg^{-1} DM for those fertilized with 1.0 kg Zn ha^{-1}. In the case of maize grown in the two other zinc treatments (i.e., 0.5 and 1.5 kg Zn ha^{-1}), Zn concentration was close to 80 mg kg^{-1} DM.

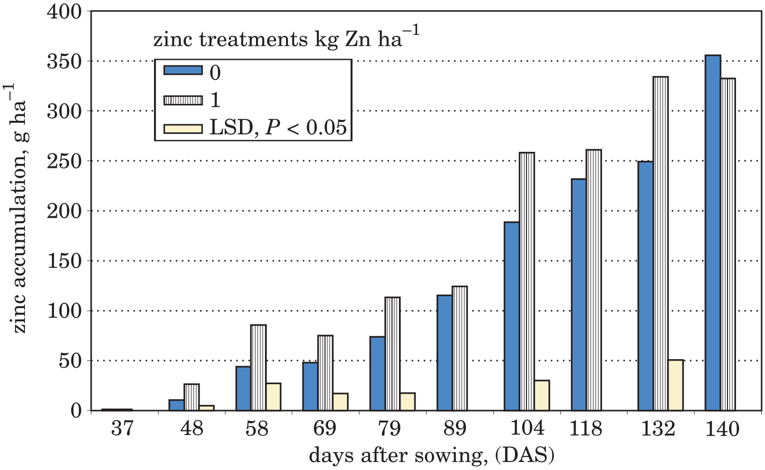

Fig. 1. Effect of zinc application on its total accumulation in the course of the vegetative season

Table 1

Effect of zinc rates on zinc concentration in maize leaves during vegetation, mean for 2002-2003 (mg kg^{-1} DM)

Growth stages (BBCH code)	Zinc treatments, kg ha^{-1}				LSD $P \le 0.05$
	0.0	0.5	1.0	1.5	
17	34.9	79.9	86.9	76.7	10.78
19	29.4	45.9	67.1	43.4	13.02
39	20.6	25.1	24.9	29.0	3.26
59	21.5	23.5	33.0	35.3	5.29
67	19.1	15.8	19.9	20.8	2.65
75	19.4	21.8	20.3	21.3	–
83	11.0	13.4	15.2	20.2	3.12
87	12.3	16.3	15.1	16.0	–
89	15.6	11.7	10.6	10.4	3.52

In the second time-phase, extending from full flowering (BBCH 67) up to full milk grain maturity (BBCH 75), plants fertilized only with nitrogen increased zinc uptake by 163%. At the same time, plants fertilized with zinc at the rate 1.0 kg Zn ha^{-1}, almost doubled zinc accumulation, i.e., increased its uptake by 207%. Further increase was much lower and stage to stage variable among the treatments. However, the final uptake of zinc by plants grown in these two distinct zinc treatments was almost the same and did not show any significant differences. The general Zn uptake (U_{Zn}) trend over the whole reproductive phase of maize growth, in spite of stage to stage variability, can be described using the linear regression model:

1. Control: $U_{Zn} = 4.05DAS - 244.0$ for $R^2 = 0.91$; $n = 5, P \leq 0.01$
2. Zinc plots: $U_{Zn} = 3.87DAS - 189.1$ for $R^2 = 0.88$; $n = 5, P \leq 0.01$

where: DAS represents days from sowing

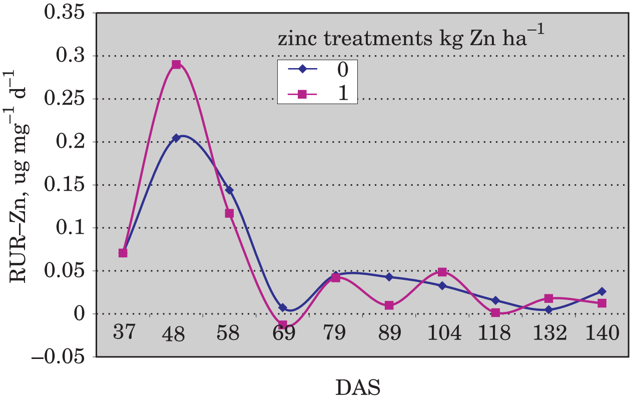

Fig. 2. Relative uptake rate of zinc by maize plants in the course of the vegetative season

The significant effect of zinc application on its own uptake was confirmed by the analysis of kinetics of its accumulation. As shown in Figure 2, for both treatments, the highest values of the Relative Uptake Rate of zinc (RUR_{Zn}) were found for the period extending from the stage of 7th to 9th leaf (BBCH17 to BBCH 19). At BBCH 17, the RUR_{Zn} for Zn-treated plants was 30% higher in comparison to the control ones. From this particular stage onwards, the studied parameter showed a declining trend, even reaching negative values for the Zn-fertilized plants. At tasselling, both groups of plants increased their RUR_{Zn} values, implying a signal of high requirements for zinc of newly growing organs or tissues. During the whole reproductive phase of maize growth, values of RUR_{Zn} were low and showed constant declining tendency, as was found for the control plot. However, plants treated with zinc showed smooth variability, raising the RUR_{Zn} at full milk stage of kernels growth (BBCH 75). The importance of this stage for maize general growth was confirmed by the analysis of Crop Uptake Rate of zinc (CUR_{Zn}). The calculated indices generally showed extremely high variability over the course of the growing season. However, at this particular stage, plants fertilized with zinc accumulated Zn at a rate of 900 mg $m^{-2}d^{-1}$, but those from the control treatments reached only 500 mg Zn m^{-2} d^{-1} (Figure 3).

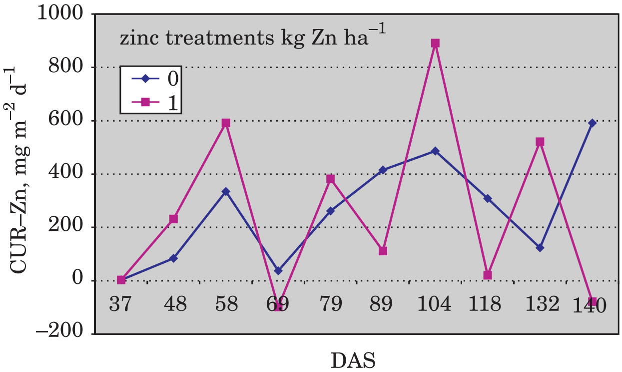

Fig. 3. Absolute uptake rate of zinc by maize crop in the course of the vegetative season

Structure of zinc accumulation

Four parts of maize plants were considered in order to evaluate the time course of zinc uptake and its partitioning. General structure of zinc partitioning among leaves, stems, cobs and kernels are shown in Figures 4a and 4b, for control and zinc treated plants, respectively. These two treatments were chosen as presenting completely distinct patterns of yield structure elements (Grzebisz et al., this issue).

Leaves require special attention due to their production and diagnostic functions. For 7 out of 9 samplings, in the course of the growing season, higher Zn concentrations were always noted for Zn-treated plants (Table 1). The highest Zn concentrations were found at vegetative stages of maize growth, i.e., from the stage of 7^{th} leaf up to the stage of 9^{th} leaf. From the stage of 9^{th} leaf onwards, the concentrations of zinc in leaves showed a declining trend, best described by means of a quadratic function. Zinc concentration in plants fertilized with 1.0 and 1.5 kg Zn ha^{-1} reached the lowest values at the end of the vegetation. For plants grown on the control plot and fertilized only with 0.5 kg Zn ha^{-1}, the lowest concentrations were noted at the beginning of the dough stage of kernels growth. However, this specific behavior of leaves should not be treated as a classical exemplification of the *law of dilution*, because the total zinc content in leaves progressed up to full milk of kernels maturity (BBCH 75) – Figure 4a. It was observed from this particular stage onwards that the amount of zinc in leaves slightly declined while its quantity in grains increased remarkably. This quasi *leaf zinc dilution effect* reflects mainly the permanent process of maize leaf extension in the course of the growing season and could be termed as *internal zinc remobilization*. Therefore, leaves could not be treated as an important source of zinc for developing kernels. However, in the period from the stage of 9^{th} leaf (BBCH 39) up to tasselling (BBCH 59) a high decrease in zinc content in leaves

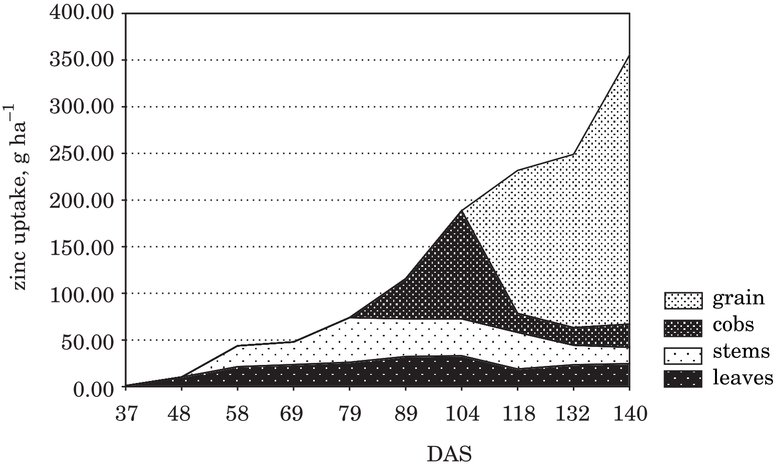

Fig. 4a. Redistribution of zinc among organs of maize in the course of the growing season – the zinc control (N)

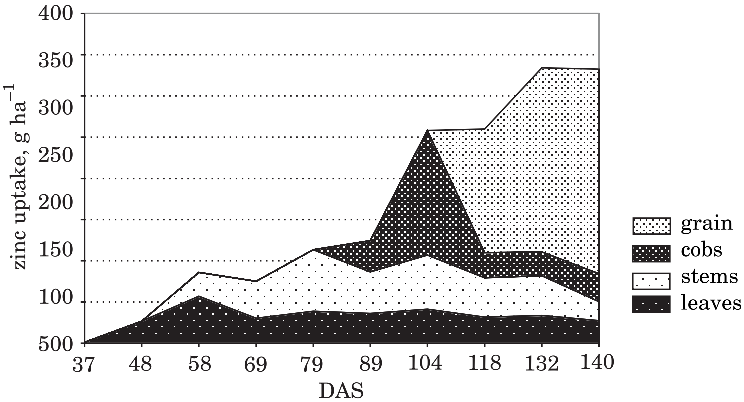

Fig. 4b. Redistribution of zinc among organs of maize in the course of the vegetative season – the zinc treatment (N+Zn)

and simultaneously sharp rise in stems occurred. This is the clearest indicator of zinc remobilization from leaves. It could be related to pollen production by tassels (WESTGATE et al. 2003).

Stems were a much more important source of zinc for developing reproductive organs, which reached the maximal Zn accumulation at tasselling (Figure 5b). From this particular stage of maize growth up to full maturity, the amount of zinc in these organs decreased by 50% in the case of plants grown in the zinc control treatment, and down to 40% for plants fertilized with zinc (1.0 kg ha^{-1}). It is necessary to point out that extended remobilization of this nutrient from vegetative organs occurred

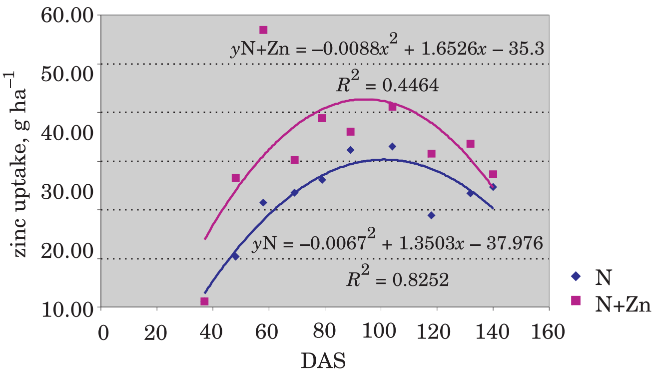

Fig. 5a. Dynamics of zinc accumulation by maize organs in the course of the vegetative season – leaves

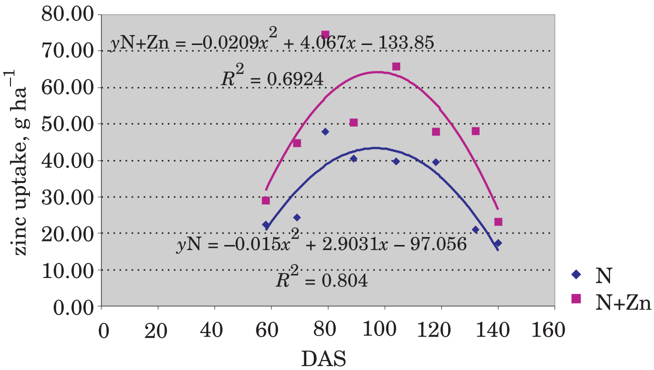

Fig. 5b. Dynamics of zinc accumulation by maize organs in the course of the vegetative season – stems

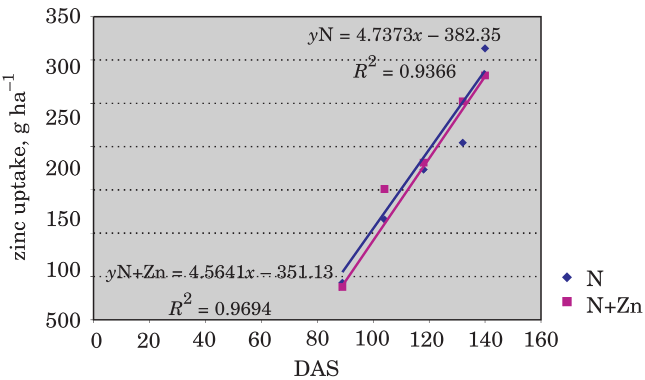

Fig. 5c. Dynamics of zinc accumulation by maize organs in the course of the vegetative season – cobs

at the beginning of the dough stage of kernels maturity. At this stage, zinc treated plants increased Zn uptake by 90 g ha^{-1}, whereas those grown on the control plot by *ca* 20 g Zn ha^{1}. However, plants from the latter treatment showed the same trend albeit one stage later, but without any effect on yield.

In general, both vegetative organs were only a minor source of zinc to growing kernels. During the reproductive phase of maize growth, soil was the main zinc source for plants. Therefore, at the grain filling period, irrespective of the studied treatment, maize plants showed extremely high requirements for zinc, as presented by the linear trend of accumulation in growing cobs (Figure 5c). Therefore, the patterns of zinc uptake by maize plants at the reproductive phase were generally very similar. Amounts of zinc taken up from soil resources by maize plants during this phase contributed to 76% and 66% of the total uptake by plants fertilized with N and N + Zn, respectively.

DISCUSSION

The main question of this study is when and how zinc fertilizer applied to maize foliage affects its yield. In order to obtain a reliable answer to these questions, the study focused mainly on patterns from two quite distinct treatments, i.e., zinc control, which relates to standard farmer's practice and the 1.0 kg Zn ha^{-1} treatment as a new optimum standard (Grzebisz et al. this issue). As recorded by Wrońska et al. (2007), the optimal timing for zinc application to maize foliage extends from BBCH 0 to BBCH 17. Maize plants well supplied with zinc at this particular stage have significantly increased the number of kernels per ear and in turn grain yield.

The second question refers to the practical importance of zinc application to maize plants cultivated on soils rich in available zinc (an assessment based on DTPA extract, Lindsay 1978). The current study revealed that in spite of high zinc availability maize plants responded to fertilizer zinc and yielded 10-20% higher that those cultivated without zinc (Grzebisz et al. this issue, Fecenko, Lozek 1998, Wrońska et al. 2007 and Potarzycki, personal communication). The maize crop response to fertilizer zinc determined in our study implicates a problem of soil and plant tests reliability. According to Schulte and Kelling (2000), the optimum Zn concentration range in maize leaves at the stage of 7^{th} leaf (BBCH 17) is 20–60 mg kg^{-1}. The data obtained in the current experiment indicate that only plants grown without zinc fertilizer dressing were within this range. However, the highest grain yield was related to Zn leaf concentration above 80 mg kg^{-1} and referred to the Zn rate of 1.0 kg Zn ha^{-1}. Therefore, the present indices of soil and maize plant nutritional zinc status need to be revised urgently. Maize crop requirements for zinc are much higher and at the time much more sophisticated than those currently recommended to farmers.

These specific patterns of zinc accumulation by maize plants, as described by the two uptake kinetic parameters such as RUR and CUR, clearly stress the importance for this crop *hot yield responsive phases*, which are time interrelated. The first one, which could be termed *primary*, stresses two facts (i) the highest requirement for zinc at early stages of maize development (ii) and its extra extension due to external supply of zinc. The relative uptake rate of zinc (RUR) by any individual maize plant treated with fertilizer zinc increased by 30%, and was the best indicator for zinc requirement of newly growing maize organs. This can be related to the stage of ovules initiation in developing cobs. The outlined hypothesis is supported by the current physiological data (ELMORE, ABENDROTH 2006). According to the authors, these stages of maize growth are very important and even decisive for building up potential numbers of ovules per row and per cob. Hence, the physiological role of zinc can be related to the potential increase of the number of ovules per cob, which is a prerequisite of kernel sink size during grain filling. The second *hot phase*, which could be termed *secondary*, but a major one, occurred at full milk grain maturity and is considered to reflect the size capacity of kernels for carbohydrates. The third one, minor, took place at tasselling, as indicated by a sharp rise of zinc concentration in the stem and was probably responsive to pollens production (WESTGATE et al. 2003).

Leaf longevity is of great importance for maize kernel weight as a factor responsible for production of carbohydrates (RAJCAN, TOLLENAAR 1999, POMMEL et al. 2006). The effects of fertilizer zinc on kernels sink capacity for carbohydrates were confirmed by generally higher thousands kernels weight (TKW). According to GULIEV et al. (1992), maize plants well supplied with zinc expresses higher activity of carbonate anhydrase, which is turn is responsible for the photosynthetic activity of leaves.

CONCLUSIONS

1. Maize plants showed the highest sensitivity to zinc at three different stages of growth, (i) from 7 to 9th leaf stage (ii) at tasselling (iii) during milk stage of kernels growth.

2. These three critical phases of kernels yield formation are a key to increasing the yielding potential of maize.

3. Vegetative organs of maize were only minor sources of zinc for growing kernels; the majority of zinc in kernels was taken up by maize plants during grain filling, directly from the soil.

4. Both soil and plant tests generally overestimate the actual zinc nutritional status of maize. Therefore, revision of such tests is urgently needed.

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