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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 II. Nitrogen uptake and dry matter accumulation patterns

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Abstract

A two-year field trial was carried out in order to outline reasons of maize grain yield increase due to foliar application of zinc, and to evaluate its effects on the dynamics of nitrogen and dry matter accumulation in the course of the growing season. Growth analysis methods were applied to describe the trends exhibited by the canopy and plant's growth. Maize plants fertilized with zinc were able to increase the rate of nitrogen uptake, as indicated by the values of absolute crop uptake rate for N (CUR-N), at two distinct time-separated phases of growth, i.e., (i) from 7th to 9th leaf and (ii) from milk to physiological maturity of kernels growth. Physiological processes occurring in these two time-separated phases resulted in an increase of maize yielding capacity. The effect of zinc as recorded in the first phase resulted in extension rate of new organs or tissues ingrowth, as confirmed by the RGR analysis. At the reproductive phase of maize growth, plants well supplied with zinc accumulated more nitrogen, which was a prerequisite for significantly higher rate of dry matter accumulation, as confirmed both by CGR and RGR analyses. The amount of extra nitrogen taken up by Zn treated plants was sufficiently high to increase grain yield by 1.5 t ha^{-1}, which was achieved in the conducted experiment.

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K e y w o r d s: growth analysis, absolute crop growth rate (CGR), relative plant growth rate (RGR), maize, nitrogen, dry matter.

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

Cz. II. Wzorce pobierania azotu i akumulacji suchej masy

Abstrakt

Dwuletnie doświadczenie polowe przeprowadzono w celu wyjaśnienia przyczyn wzrostu plonu ziarna kukurydzy dolistnie traktowanej nawozem cynkowym i oceny jego wpływu na dynamikę procesów akumulacji azotu i suchej masy w okresie wegetacji. Do opisu uzyskanych trendów zastosowano metody analizy wzrostu łanu i rośliny. Kukurydza nawożona cynkiem była w stanie, jak wykazały wartości wskaźnika absolutnej szybkości pobierania azotu przez łan (CUR-N), zwiększyć pobieranie azotu w dwóch czasowo różnych fazach rozwoju, to znaczy (i) od fazy 7. do 9. liścia oraz (ii) od fazy dojrzałości mlecznej do fizjologicznej ziarniaków. Procesy fizjologiczne ujawniające się w tych dwóch czasowo odległych fazach rozwoju kukurydzy determinowały wzrost potencjału produkcyjnego kukurydzy. Działanie cynku w pierwszej fazie przejawiło się wzrostem szybkości akumulacji azotu, który spowodował wydłużenie fazy intensywnego przyrostu nowych tkanek lub/i organów, jak potwierdziła analiza RGR. W fazie reproduktywnej rozwoju kukurydzy rośliny dobrze odżywione cynkiem akumulowały azot z większą szybkością, co było podstawowym warunkiem zwiększonej akumulacji suchej masy, potwierdzonej analizami CGR i RGR. Ilość azotu pobranego ekstra przez rośliny nawożone cynkiem była dostatecznie duża do wzrostu plonu ziarna o 1,5 t ha^{-1}, co uzyskano w przeprowadzonym eksperymencie.

S ł o w a k l u c z o w e: analiza wzrostu, absolutna szybkość wzrostu łanu, względna szybkość wzrostu łanu, kukurydza, sucha masa, azot.

INTRODUCTION

Agricultural production is under permanent pressure of abiotic and biotic stresses, negatively affecting plant crops growth and yields (Mittler 2006). On the other hand, the inefficient use of nitrogen fertilizers is of great concern to the environment and human health (Cakmak 2002, Townsend et al. 2003). Maize requirements for nutrients, in spite of its high yielding potential, are comparable to other cereals (Sturm et al. 1994). The decisive effect of nitrogen on plant growth and yielding of cereal crops is well known. However, nitrogen recovery efficiency of maize in farm production is generally low, in the range from 20 to 40% (Roberts 2006). This finding is supported by scientifically developed *production functions for nitrogen*, which stresses a moderate scale of maize response to the applied fertilizer N. This syndrome of maize response to nitrogen is termed as *the smooth reaction* (Fotyma 1994).

In the light of great challenges and simultaneous low utilization of fertilizer nitrogen, the main target to maize growers is to search for factors which may increase both the uptake and utilization-efficiency of the applied fertilizer N. The actual yield increase of crop plants, including maize, can be therefore achieved by ameliorating the factors decisive for nitrogen use efficiency (SINCLAIR et al. 2004, ROBERTS 2006). Among micronutrients, zinc plays a great metabolic effect on plant economy and nitrogen efficiency, as has been recognized by plant biochemists and physiologists (MARSCHNER 1986, CAKMAK 2002).

The harvested yield of a given crop plant, including maize, and its yield components reflect, but only *ex post*, conditions of dry matter accumulation over the growing season (RAJCAN, TOLLENAAR 1999). Therefore, the plant growth analysis seems to be a reliable scientific tool for discriminating the most sensitive stages of maize plants growth to external factors, including supply of nutrients, for example zinc. Unfortunately, the quantitative effects of Zn on maize yielding physiology are poorly recognized.

The objective of the present studies was to determine the effects of foliarly applied zinc on nitrogen and dry matter accumulation dynamics over the course of maize crop growth.

MATERIAL AND METHODS

The general design and experimental details of this study are reported by GRZEBISZ et al., (Part I, this issue). Plants growth analysis was applied as an analytical tool in order to explain the quantitative effect of zinc on dry matter accumulation by maize. Two kinetic parameters of crop growth were calculated, i.e., absolute Crop Growth Rate (CGR) and Relative Growth Rate (RGR). In the same way, kinetic parameters of nitrogen uptake were calculated for nitrogen: absolute crop uptake rate – CUR_N and relative uptake rate – RUR_N. Both parameters express growth rate on a daily basis, but the former one - per unit area whereas the latter one outlines growth as an aspect of new dry matter increase per plant (HUNT et al. 2002). For details see GRZEBISZ et al. (2008).

RESULTS

Nitrogen accumulation patterns

It has been assumed that dry matter yield and the rate of its accumulation depends directly on nitrogen supply. Therefore, patterns of nitrogen accumulation were investigated in detail over the course of maize growth in the growing season. In all consecutive stages of growth, beginning at the stage of 9th leaf, higher amounts of nitrogen were recorded in plants grown in the Zn-fertilized treatments. However, in only 2 out of 10 stages of maize growth we analyzed, i.e., at the beginning of dough maturity and at the final maturity, the effect of zinc application was significant (Figure 1). At these two particular stages, the application of 1.0 kg Zn ha^{-1} increased N uptake by 39.0 kg ha^{-1} and 46.4 kg N ha^{-1}, respectively, versus the control. In addition, during these two consecutive reproductive stages, plants progressed nitrogen uptake, irrespective of the experimental treatments. Nitrogen uptake by maize plants grown on the control plots increased from 150.0 to 202.5 kg ha^{-1} and on the plots fertilized with 1.0 kg Zn ha^{-1}, from 188.3 to 248.9 kg ha^{-1}. Hence, it can be concluded that maize crop accumulated nitrogen progressively to the end of its growth. Nitrogen accumulation trends over the course of the growing season followed the linear regression model:

1. Zn control $U_N = 2.05DAS - 89.13$ $R^2 = 0.96$; $n = 10$, and $P \leq 0.001$
2. Zn treatment $U_N = 2.54DAS - 114.55$ $R^2 = 0.97$; $n = 10$, and $P \leq 0.001$

where:

U_N – nitrogen uptake, kg N ha^{-1};
DAS – days after sowing.

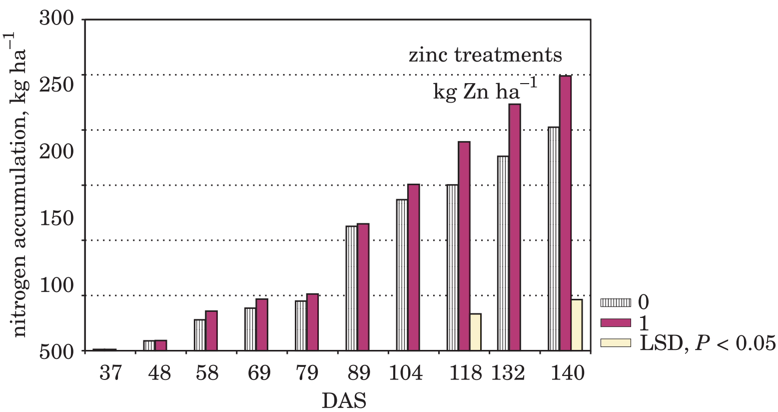

Fig. 1. Effect of zinc application on nitrogen accumulation by maize in the course of the growing season

Plants fertilized with zinc showed a much higher rate of nitrogen accumulation, as indicated by the direction coefficients of the equation developed for Zn treatment.

Plants treated with zinc at the early stage of maize growth have significantly accelerated their rate of nitrogen accumulation. A very distinct shape of curves describing parameters of crop uptake rate for nitrogen (CUR_N) was determined. As shown in Figure 2, the most critical time-point of maize plant nitrogen economy was the onset of flowering. Within a period of 10 days, from tasselling till full flowering, amounts of nitrogen accumulated by maize plants have almost doubled (Figure 1). This high increase was attributed to a manifold increase of CUR_N, from *ca* 50 to 650 g m^{-2} d^{-1}, irrespective of the experimental treatments. However, ef-

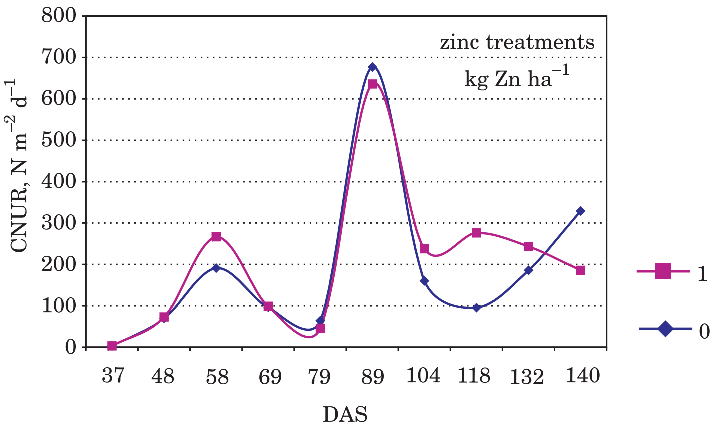

Fig. 2. Effect of zinc application on absolute nitrogen uptake rate by maize crop in the course of the growing season

fects of zinc were found in two significant stages of maize growth. The first one, minor, appeared at the stage of 9^{th} leaf, whereas the second one, considered major, started at the beginning of full milk maturity and extended up to the physiological maturity of maize. The rate of nitrogen accumulation by Zn-treated plants, estimated on the basis of CUR_N, was higher than on the control plot, by 48% at full milking stage, 88% at the beginning of the dough maturity and 31% at physiological maturity. However, the relative uptake rate values for N (RUR_N) did not show any differences in the rate of nitrogen accumulation by maize plant due to the experimental treatments (Figure 3). Nevertheless, two main *hot points* of nitrogen uptake patterns were discriminated on the basis of RUR_N parameters. The first one, major, appeared from the stage of 7^{th} to 9^{th} leaf and the second one, minor, occurred from tasselling (BBCH 59) to full flowering (BBCH 67).

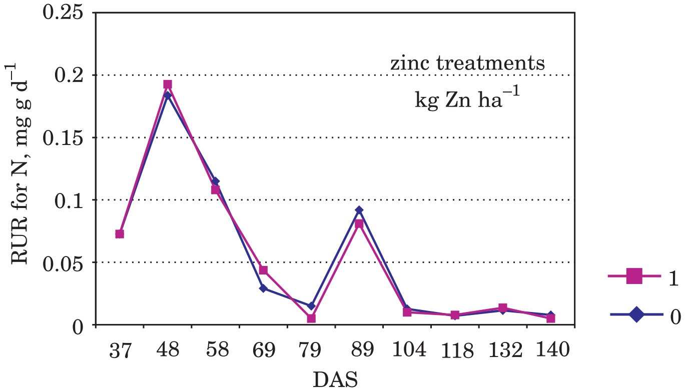

Fig. 3. Effect of zinc application on relative nitrogen uptake rate by maize crop in the course of the growing season

Dry matter accumulation patterns

The yields of dry matter of maize crop increased progressively over the growing season, reaching maximum at full maturity (BBCH 89) for both studied treatments (Figure 4). Zinc stimulated the accumulation of dry matter since the stage of 9th leaf (BBCH 19), although a significant effect was noticed first at the stage of full milking growth of kernels (BBCH 75). Dry matter accumulation by plants increased progressively in all the consecutive stages of growth, but an especially high rise was observed from flowering (BBCH 67) to the beginning of dough kernels maturity (BBCH 83).

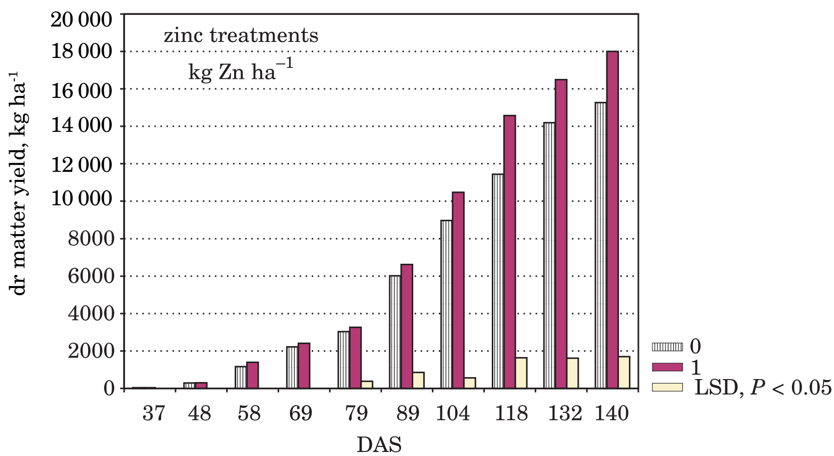

Fig. 4. Effect of zinc application on dry matter accumulation by maize in the course of the growing season

The rate of dry matter accumulation by maize, as expressed by crop growth rate parameters (CGR), achieved its maximum at full flowering (BBCH 67) – Figure 5. During a period of 10 days, i.e., from tasselling to full flowering, plants increased almost 4-fold their rate of growth, irrespective of the studied treatments. This increase is time-related to the rise of RUR_N, reflecting a huge rate of new tissue ingrowth. In the period of 4 weeks following tasselling, plants fertilized with zinc accumulated dry matter yield at a much higher rate than those grown on the control plot, i.e., without external zinc supply. The CGRs values of Zn-treated plants were higher at full flowering by 25%, at milk maturity by 31%, and at the beginning of dough maturity by 65%, as compared to the control plants. These data clearly stress higher *sink* potential of zinc fertilized plants to accumulate carbohydrates by developing kernels.

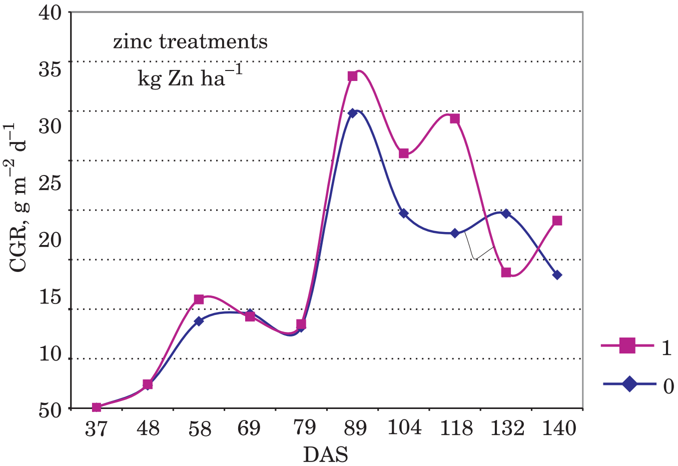

Fig. 5. Effect of zinc application on absolute crop dry matter growth by maize crop in the course of the growing season

The analysis of maize growth by means of relative growth rate (RGR) parameters revealed that zinc application stimulated dry matter accumulation in two distinct growth periods (Figure 6). Generally, an individual plant expressed its own highest rate of growth at the stage of 7th leaf, followed by a gradual decline, reaching the lowest values at maturity. However, plants fertilized with 1.0 kg Zn ha^{-1}, were able to keep the highest rate of growth during the next 10 days following the stage of 7th leaf. At the stage of 9th leaf, Zn-treated plants accumulated dry matter 3-fold faster than those grown on the control plot. An identical trend, albeit less pronounced, was found during the full milk stage of maize growth.

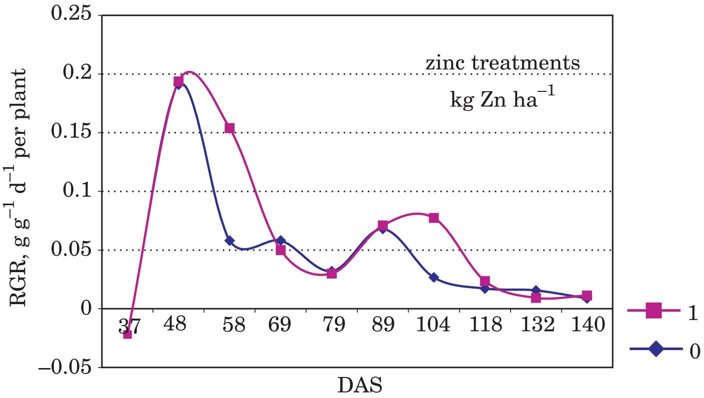

Fig. 6. Effect of zinc application on relative growth rate of maize plant in the course of the growing season

DISCUSSION

The main concept regarding the actual yield of maize crop is considered by plant physiologists as a ratio between *sink size*, i.e., an ability of a developing cob to accumulate assimilates, and *source size*, supply of nitrogen and assimilates as well (UHART, ANDRADE 1995, CAZETTA et al. 1999). JONES et al. (1996) reported that two plant characteristics, i.e., kernel number (per) plant (KNP) and plant growth rates, in the period of 4 weeks, beginning one week before silking, are decisive for establishing the final grain yield of maize. This statement is in close agreement with the results obtained in our study and reflects the processes responsible for cob sink capacity build up during preanthesis and postanthesis cob growth.

The main difference between the maize treatments studied occurred first in the vegetative phase of maize growth, around the stage of 7^{th} leaf. At this particular stage, plants well supplied with zinc (i.e., 1.0 kg Zn ha^{-1}) increased zinc concentration in leaves 2.5-fold in comparison to the control ones, i.e. fertilized only with nitrogen (GRZEBISZ at al. 2008). Consequently, maize plants fertilized with zinc accelerated (i) the uptake rate of nitrogen (ii) and new biomass ingrowth. But both processes were not conducted by plants simultaneously. The increased plant uptake rate of zinc and nitrogen took place at the same stage of maize growth, i.e., at the 7^{th} leaf. At this particular stage, plants fertilized with zinc increased uptake rate of nitrogen in comparison to the control plants by 40%. Consequently, these plants were in position to continue their very high growth rate (RGR), i.e. ingrowth of new biomass up to the stage of 9^{th} leaf. The high dependency of the relative uptake rate for nitrogen – RUR_N (y) on the relative supply of zinc – RUR_{Zn} (x) was confirmed by the linear type relationships:

1. Zn control $y = 0.85x + 0.005$ $R^2 = 0.86$ $n = 10$; $P \leq 0.01$
2. Zn treatment $y = 0.59x + 0.019$ $R^2 = 0.76$ $n = 10$; $P \leq 0.05$

The specific plant responses to zinc we discovered had a significant effect on plant growth in consecutive growth stages, appearing again during the reproductive phase, from flowering up to full milking stage of kernels. Hence, the physiological role of zinc can be related to the potential increase of the number of ovules per cob, as related to current nitrogen supply, indicated by the CUR data for nitrogen. This particular stage for a growing maize plant is decisive for the ovules in row formation (ELMORE, ABENDROTH 2006). This hypothesis is supported by SUBEDI, MA (2005), who found that nitrogen deficiency before BBCH 18 (stage of 8th leaf) resulted in decreasing cob length and number of kernels per cob.

In addition, there was a tremendous increase in the uptake rate of zinc followed the highest values of CUR for N, which occurred at full anthesis. Therefore, plants well supplied with zinc in the vegetative growth period were able to accumulate more nitrogen in the most critical stage of kernels development, i.e., 2 weeks after pollination. At that time, the availability of nitrogen is decisive for division of endosperm cells and initiation of starch granules (JONES at al. 1992). At these particular stages, maize plants well supplied with nitrogen significantly increased the absolute rate of nitrogen uptake from soil resources. At the final maturity, these plants accumulated *ca* 46 kg N ha^{-1} more than those grown on the control plot, i.e., fertilized only with N. Based on the specific uptake of nitrogen as 20 or 30 kg N per 1 tone of kernels with appropriate amounts of straw (WICHMANN 1996/2006), one may calculate the yield increase, which in this particular case was up to 2.32 and 1.55 t ha^{-1}, respectively, due to higher zinc availability.

The plant behavior we observed should not be related to the current Zn uptake but to increased kernels sink capacity, established at preanthesis stages of maize plants growth. These processes progressed efficiently under non-limited availability of nitrogen. Another aspect of our experiments refers to leaf longevity, a factor of great importance for maize kernel rate of growth and final weight (RAJCAN, TOLLENAAR 1999, POMMEL et al. 2006). Higher uptake of nitrogen by Zn-treated plants was probably a prerequisite of higher longevity of maize leaves, which in turn were capable to increase their rate of photosynthesis (GULIEV et al. 1992.

CONCLUSIONS

1. Zinc fertilizer application at an early stage of maize growth accelerated the plant rate of zinc accumulation at the stage of 7th leaf, and,

in turn, increased the rate of crop nitrogen uptake, a factor decisive to the formation of ovules, i.e., potential kernels number per row.

2. At the reproductive phase of maize growth, plants well supplied with zinc accumulated more nitrogen at the most critical stages of kernels development, just 2 weeks after pollination, which is crucial for both the vitality (number) and the size of an individual kernel.

3. The main reason of higher uptake of nitrogen by plants well supplied with zinc was probably extended longevity of leaves, producing in turn enough carbohydrates to supply developing kernels.

4. Modern maize cultivars of high yielding potential, even cultivated on soils rich in available zinc, may respond significantly to fertilizer zinc, increasing grain yield even up to 20%.

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