Effect of zinc foliar application on grain yield of maize and its yielding components

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ABSTRACT

Actual yields of maize harvested by farmers are at level much below attainable yield potential of currently cultivated varieties. Among many growth factors zinc was recognized as one of main limiting factors of maize crop growth and yielding. This hypothesis has been verified within a three-year field study, where zinc fertilizer was applied to maize plants at the 5th leaf stage. Maize crop responded significantly to zinc foliar application in two of three years of study. The optimal rate of zinc foliar spray for achieving significant grain yield response was in the range from 1.0 to 1.5 kg Zn/ha. Grain yield increase was circa 18% (mean of three years) as compared to the treatment fertilized only with NPK. Plants fertilized with 1.0 kg Zn/ha significantly increased both total N uptake and grain yield. Yield forming effect of zinc fertilizer revealed via improvement of yield structure elements. The number of kernels per plant showed the highest response (+17.8% as compared to the NPK plot) and simultaneously the highest dependence on N uptake (R^2 = 0.79). For this particular zinc treatment, however, the length of cob can also be applied as a component of yield structure significantly shaping the final grain yield.

Keywords: maize; zinc foliar application; grain yield; nitrogen uptake; yield structure components

Maize grain yield potential (GYP) is twice as high as compared to other cereal crops (Tollenar and Lee 2002). However, even if quantitative requirements for nutrients are almost the same (Benton Jones 2003), actual harvested yields are low. For the 2002–2004 periods, world average yields of maize and winter wheat were estimated for 4.57 and 2.77 t/ha, respectively (FAOSTAT 2005). In Poland, the attainable yield of maize (AY) is in the range from 11.0 to 13.0 t/ha, but actual yields are much lower, circa 50% of the AY (Michalski 2005). As recently assessed by Subedi and Ma (2009) for the humid regions of eastern Canada, weed infestation is the main factor limiting the AY (27–38% of AY reduction), followed by insufficient preplant N application (10–22%) and low plant population density (8–13%). Maize AY reduction resulting from the lack of Zn application was assessed by these authors at the level of 10%.

As well documented by plant physiologists, zinc exerts a great influence on basic plant life processes, such as (i) nitrogen metabolism – uptake of nitrogen and protein quality; (ii) photosynthesis – chlorophyll synthesis, carbon anhydrase activity; (iii) resistance to abiotic and biotic stresses – protection against oxidative damage (Alloway 2004, Cakmak 2008).

Most research on soil and foliar application of zinc focused on alleviating its deficiencies, particularly on wheat and rice cultivated in semi-arid or arid regions of the world (Alloway 2004, Cakmak 2008). Maize was recognized by farmers for a long time as a crop of high response to zinc supply. In temperate regions, due much shorter vegetation and low temperatures prevailing at early stages, maize growth appears to be highly sensitive to many external and internal stresses, which in turn induce grain yield reduction (Leach and Hameleers 2001, Subedi and Ma 2009). It was recently documented that zinc foliar application is a simple way for making quick correction of plant nutritional status, as reported for wheat (Erenoglu et al. 2002) and maize (Grzebisz et al. 2008).

Based on recent investigations related to factors limiting maize yielding physiology as well as grain yield, a hypothesis was formulated that the external supply of zinc boosts processes responsible for the yielding potential of maize.

The general objective of the study was to evaluate the yield forming potential of fertilizer zinc applied at four rates to maize leaves at early stage of plant growth. The specific purpose was to exhibit Zn-induced effect on grain yield via quantifying nitrogen uptake and yield structure components.

MATERIALS AND METHODS

Physical and chemical characteristics of soils. Field experiments were carried out during three consecutive years 2001, 2002, 2003 at an agricultural farm located in Nieczajna (25 km north of Poznań, Poland; 52.40°N, 16.49°E; 90 m above the sea level). Soils in the experimental site are developed from postglacial loamy sand and are classified, according to the World Soil Classification (FAO), as typical Luvisols. Agrochemical soil characteristics of the experimental plots were determined each year at the beginning of the growing season.

Prior to basic analyses, soil samples were air-dried (except for N_{min}–soil mineral nitrogen determination), crushed to pass through a 1 mm mesh sieve. Granulometric composition was determined according to the aerometric method of Bouyoucos-Casagrande (Gee and Bauder 1986), and soil pH was potentiometrically measured in 1M KCl extracts at soil to solution ratio of 1:2.5, according to the Polish Standard (1994). Exchangeable and organically bound zinc (Zn) forms were extracted by the DTPA (diethylenetriaminepentaacetic acid) procedure according to Lindsay and Norvell (1978). Amounts of available phosphorus (P) and potassium (K) were assayed by the Egner-Riehm method, whereas for magnesium (Mg) the Schachtschabel method was applied (Lityński et al. 1976). Soil mineral nitrogen was extracted from moist soil samples (Houba et al. 1990) and determined colorimetrically (FIAstar 5000 Analyser). Phosphorus was determined colorimetrically (Analitykjena Specord 40), whereas K, Mg and Zn by the FAAS method (Flame Atomic Absorption Spectrophotometry, Varian 250 plus). Physical and selected chemical results are listed in Table 1.

Field experiments and plant analysis. Field experiments were established at an agricultural farm, where maize was grown under long-term monoculture. The one factorial experiment with maize (variety Bachia) with four rates of zinc: 0.0; 0.5; 1.0; 1.5 kg/ha was established in six replications. Basic experimental plot size (8.4 m × 60 m) consisted of 12 rows of plants. Foliar spray of zinc prepared according to Zn rates, at concentrations of 0.0, 1.25, 2.5 and 3.75 g Zn/dm^3 as oxysulphate (45% of ZnO and 5% of $ZnSO_4$), was applied on maize foliage at 5^{th} leaf stage. This fertilizer contains also small quantity of sulfur, amounting to 0, 10, 20 and 30 g S/ha, for consecutive treatments. Phosphorus and potassium fertilizers were applied yearly in autumn at rates of 11 kg P and 100 kg K per ha as triple superphosphate (TSP) and potassium chloride (KCl), respectively. Nitrogen as ammonium nitrate (34%) was applied as one preplant rate amounting to 135 kg/ha. Plant protection and all other agro-technologies followed standard practices.

Maize was manually harvested from an area of 14 m^2 (2 rows per 10 m) at technological maturity of kernels (circa 70% dry weight basis). Total grain yields were adjusted to 14% moisture content. At harvest each plant sample was partitioned into subsamples of grain and straw (including leaves, stems, cob sheaths) and then dried (65°C).

Partial Factor Productivity of the applied fertilizer N (PFP_N) was calculated by dividing the harvested grain yield (GY) of maize by the applied N rate, i.e. 135 kg N/ha:

$$PFP_N = GY/135 \text{ (kg grain/kg N)}$$

Table 1. Selected agrochemical characteristics of soils under investigation

Years	Depth (m)	pH	Available nutrients (mg/kg soil)				N_{min} (kg/ha)
			P	K	Mg	Zn	
2001	0.00–0.30	7.1	129	160	48	3.2	135.0[1]
	0.31–0.60	7.2	118	132	37	2.4	+ 60.7[2]
2002	0.00–0.30	6.8	140	154	59	2.8	135.0
	0.31–0.60	7.2	91	132	52	3.0	+ 55.4
2003	0.00–0.30	6.3	165	363	35	3.1	135.0
	0.31–0.60	6.5	137	272	31	2.7	+ 55.7

[1]fertilizer nitrogen; [2]soil mineral nitrogen (0.0–0.6 m)

The next agronomical parameter used for evaluating Zn effect was the Harvest index (HI), reported as grain yield divided by the total aboveground biomass (B_t):

HI = (GY/B_t) × 100% (%)

Nitrogen concentration in plant material was determined by standard macro-Kjeldahl procedure. Nitrogen harvest index (NHI) was calculated by dividing the amount of N accumulated in grain (N_{GY}) yield by total N uptake (N_t) by maize canopy at harvest:

NHI = (N_{GY}/N_t) × 100% (%)

Unit nitrogen uptake (UNU) is a parameter expressing total N accumulation by 1 t of grain and concomitant amount of N in vegetative plant crop organs at harvest. It was calculated by dividing N_t by maize grain yield (GY):

UNU = N_T/GY (kg N 1 t GY)

Yield structure components were determined on four randomly chosen cobs for each replication. The following characteristics were directly measured: (i) length of cobs (LC); (ii) number of rows per cob (NRC); (iii) number of kernels per row (NKR), and (iv) thousand kernels weight (TKW). The number of kernels per cob (NKC) was calculated by multiplying NRC and NKR.

Experimental data were evaluated by means of analysis of variance. Simple regression analysis was applied for evaluating the optimal zinc rate. Path analysis procedure was used to outline relationships between grain yield and its yielding components (Konys and Wiśniewski 1984).

RESULTS AND DISCUSSION

General growth conditions. Soil fertility, as indicated by soil characteristics, was generally favorable for maize production. Soil pH was in the neutral range during the first two years of experimentation and in the slightly acid class in the third year. The contents of available phosphorus were very high compared to potassium and magnesium, whose levels were optimal, in spite

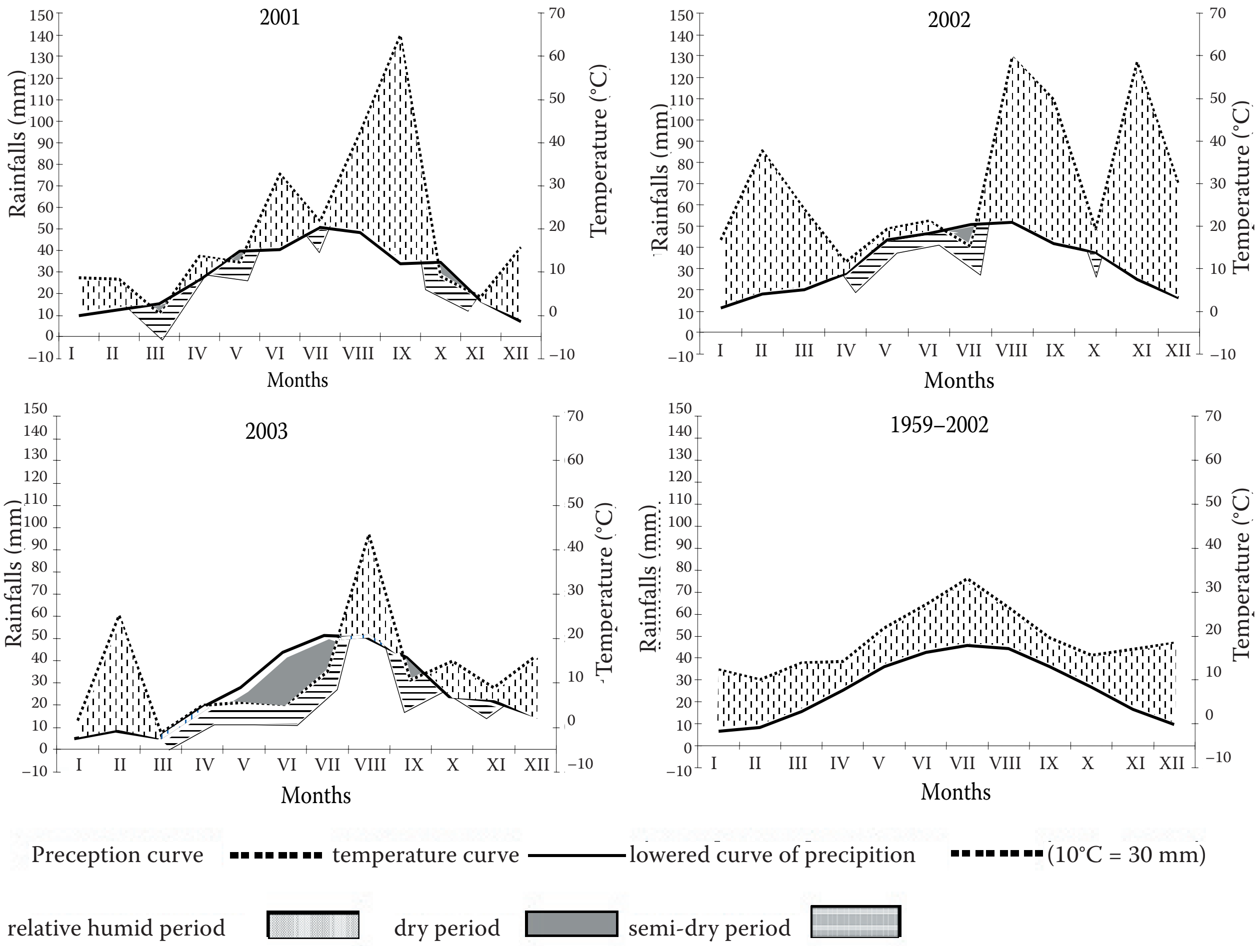


Figure 1. An assessment of meteorological conditions in years 2001–2003 on the background of long-term averages 1952–2002, (method by Walter 1976), the Brody Meteorological Station (Poland)

of year-to-year variability. The contents of available zinc were high, according to the Zn-DTPA procedure and rating (Table 1).

During the course of maize vegetation, plants growth was highly affected by water availability and temperatures (Figure 1). In 2001, the amount of rainfalls and their distribution was supra-optimal for maize growth. Such conditions induced high grain yields; on the control plot, i.e. fertilized only with NPK, they reached 9.45 t/ha while on the plot receiving also 1.0 kg Zn/ha they were 12.025 t/ha (Figure 2). The latter value is at the level of potential maize grain production in Poland (Michalski 2005). In the next two consecutive years of study, 2002 and 2003, meteorological growth factors were much less favorable, due to the deficiency of rainfalls at critical stages of maize growth. In 2002 semi-drought conditions prevailed throughout most of maize vegetative growth. In 2003 drought affected plants growth during the whole vegetative growth period and at anthesis. The occurring water shortages were combined with an increase of the average monthly temperatures (2–3°C) as compared to long-term averages. Consequently, the harvested yields were much lower, ranging from 7.0 to 8.0 t/ha for NPK treatments and from 8.0 to 9.5 t/ha for NPK plus the Zn opt treatment (Figure 2).

Grain yield characteristics. Maize grain yields, irrespective of seasonal growth conditions variability, responded each year to zinc foliar application (Figure 2). In the first year of study, maize fertilized only with NPK produced 9.45 t grain per ha. Zinc foliar spray at the stage of 5th leaf allowed to get a significant grain yield increase, by ca 16% and 27% in the treatments with 0.5 and 1.0 kg Zn/ha, respectively. In the second year of study, grain

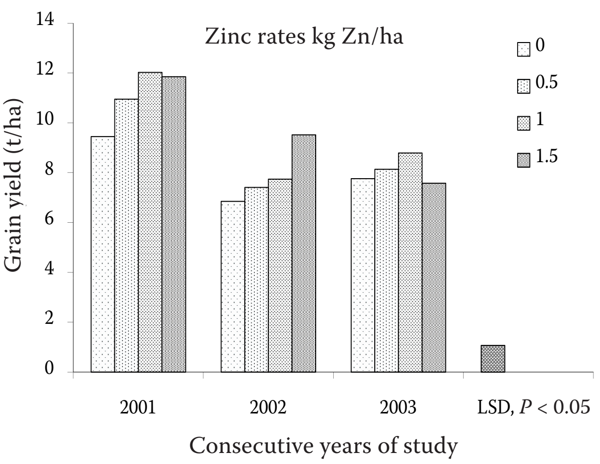


Figure 2. Effect of foliar zinc application to maize leaves at 5–6-leaf stage on grain yield

yields increased with increasing Zn rates, but a significant effect was only achieved in the treatment with 1.5 kg Zn/ha (circa 39%). In the third year, grain yield responded positively to zinc foliar addition up to 1.0 kg Zn/ha (13% yield increase), but this trend was not significant. Plants grown on the plot fertilized with 1.5 kg Zn/ha showed even an unexpected yield depression.

Two different patterns of grain yield response to Zn rates were found as presented below:

1. 2001: $Y = -1.68\ Zn^2 + 4.17\ Zn + 9.41$;
   $R^2 = 0.99$, for $n = 4$
   $Zn_{opt.} = 1.24$ kg Zn/ha and $Y_{max} = 12.0$ t/ha
2. 2002: $Y = 1.67\ Zn + 6.63$; $R^2 = 0.87$, for $n = 4$
3. 2003: $Y = -1.59\ Zn^2 + 2.41\ Zn + 7.65$;
   $R^2 = 0.74$, for $n = 4$
   $Zn_{opt.} = 1.33$ kg Zn/ha and $Y_{max} = 8.56$ t/ha

where: Y – grain yield, t/ha; Y_{max} – maximum grain yield, t/ha; Zn – zinc rate, kg Zn/ha; Zn_{opt} – optimum zinc rate, kg Zn/ha.

The calculated efficiency of fertilizer nitrogen, i.e. Partial Factor Productivity of the applied fertilizer N (PFP_N) was both year-specific and at the same significantly affected by the zinc rate. In the first year of study, the indices of PFP_N were high and showed an increase from 70 to ca 90 kg grain per kg of applied fertilizer N as calculated for the NPK control treatment and the optimum Zn rate, respectively. In 2002, the PFP_N indices were much lower but at the same time showed linear response to zinc application and rose up from 51 to 70.5 kg grain kg/N, for 0.0 to 1.5 kg Zn/ha treatments, respectively. In the third year, the calculated indices increased from 57.5 for the NPK-control to 63.4 kg/N for the optimum Zn rate. Therefore it can be concluded that foliar zinc application at early stages of maize growth, irrespective of weather conditions, increased nitrogen use efficiency of fertilizer.

The highest values of Harvest Index (HI), i.e. circa 50% of all calculated indices, were noted in the third, extremely dry 2003 year, whereas they were the lowest in the optimal 2001 year (46%). The calculated parameter indicated an effect of external zinc supply on dry matter partitioning among aboveground organs of maize plants. Foliar application of zinc exerted, irrespective of weather conditions, a very constant effect on HIs. Generally, foliar zinc application was a factor which induced a decrease of the HI by circa 5% on average as compared to NPK-control treatments (Table 2).

Nitrogen in maize vegetative biomass and grain at harvest. Total nitrogen content in maize

Table 2. Effect of zinc on maize yield structure components, mean for 2001–2003

Zinc rates (kg/ha)	Harvest index (% ± SD)	Length of cob (mm)	Number of rows per cob	Number of kernels per row	Number of kernels per cob	Thousand kernels weight (g)
0	47.9 ± 1.8	138.8 ± 0.9	14.66 ± 0.47	27.8 ± 3.9	407.0 ± 65.8	253.4 ± 11.2
0.5	41.9 ± 0.9	153.7 ± 1.4	15.00 ± 0.57	29.2 ± 2.7	438.0 ± 47.0	266.1 ± 23.4
1.0	42.9 ± 2.6	157.2 ± 1.2	15.13 ± 0.44	31.7 ± 4.3	479.5 ± 64.9	264.3 ± 18.3
1.5	43.2 ± 6.3	151.9 ± 1.5	15.04 ± 0.46	29.4 ± 3.2	441.7 ± 59.0	275.0 ± 24.7
LSD ≤ 0.05	–	4.24	n.s.*	2.32	34.30	9.74

*not significant

plant parts at harvest, both in grain and straw showed small variability in spite of high year-to-year rainfall fluctuations (Table 3). Much higher variability of N contents was however imposed by rates of foliar zinc application. In the case of this particular growth factor (i.e. N) two general rules were observed. The first one refers to the content of total N in maize plants fertilized with 0.5 kg Zn/ha where a significant decline was observed as compared to the NPK fertilized plants. This trend was much more pronounced for grain than for straw. The second rule was revealed in the treatment with 1.0 kg Zn/ha. Maize plants well supplied with zinc were able both to increase grain yield and to maintain total N contents at levels presented by plants grown on the NPK-control.

Total nitrogen uptake (N_t) by maize canopy at harvest showed high quantitative variability both due to weather and rates of applied zinc (Figure 3). Maize responded to water shortage as shown by a significant decrease in the amounts of nitrogen taken up by maize crop affected by drought during the vegetative season. At the same time, amounts of nitrogen accumulated in maize canopy at harvest were significantly modified by zinc foliar spray. Only in the first year, the lowest rate of zinc, i.e. 0.5 kg Zn/ha significantly affected total nitrogen uptake as compared to the NPK-control. In other years of study a significant increase of N_t uptake was found only in the treatment with 1.0 kg Zn/ha. The effect of 1.5 kg Zn/ha was positive and significant, but only in the first two years. The increase of total nitrogen uptake induced by zinc application corroborates the thesis of its primary effect on main physiological processes, related to nutrients uptake (Alloway 2004).

The observed patterns of nitrogen partitioning among plant parts at harvest depended on the amount of nitrogen additionally taken up by plants. The found phenomena are corroborated with two simple post-harvest indices. The first one, termed Nitrogen Harvest Index (NHI) describes nitrogen distribution at harvest among grain and vegetative maize organs. As a rule, its values were lower by 4–6% on all plots receiving zinc (Figure 3). Under conditions of sub-optimal zinc rate, i.e. 0.5 kg Zn/ha, maize plants were able to increase grain yield, but in turn inducing a decline of N accu-

Table 3. Total nitrogen content in plant parts (%), unit nitrogen uptake at harvest (UNU) and partially factor of fertilizer nitrogen productivity (PFP_N)

Zinc rates (kg Zn/ha)	2001		2002		2003		PFP_N[1] (kg ± SD)	UNU[2] (kg N ± SD)
	G[3]	S[3]	G	S	G	S		
0.0	2.19	0.81	2.26	0.76	2.03	0.75	59.5 ± 8.9	30.1 ± 1.9
0.5	2.08	0.71	1.99	0.74	1.69	0.66	65.4 ± 13.1	29.2 ± 1.9
1.0	2.12	0.76	2.10	0.81	2.09	0.68	70.5 ± 15.3	31.9 ± 2.3
1.5	2.03	0.71	1.94	0.77	1.72	0.71	71.5 ± 14.2	28.8 ± 4.1

[1]partially factor of fertilizer nitrogen productivity (PFP_N), kg grain per 1 kg N fertilizer; [2]unit nitrogen uptake (kg N/1 t of grain, including concomitant amount of N in vegetative organs); SD – standard deviation; [3]grain and straw (vegetative parts of maize plant) at harvest

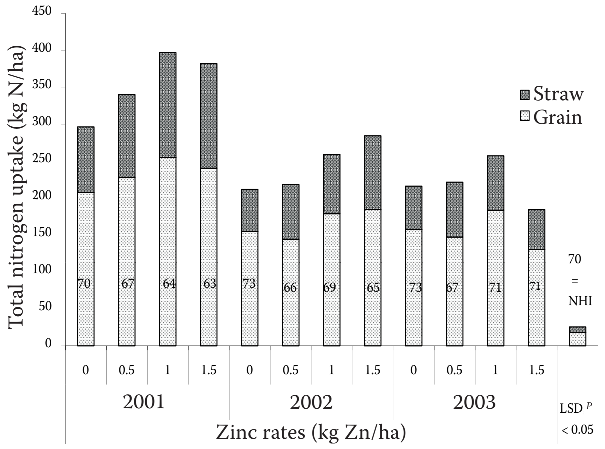


Figure 3. Effect of zinc foliar application to maize leaves at 5–6-leaf stage on total nitrogen uptake

mulation in grain (N_g). However, plants fertilized with 1.0 kg Zn/ha showed quite different behavior. They were able both to increase grain yield, i.e. to increase amount of produced dry matter, and to accumulate more nitrogen per unit of grain yield. The next index, i.e. Unit Nitrogen Uptake (UNU), revealed general sensitivity of a maize canopy to total N supply. The highest UNU index was achieved on the plot fertilized with 1.0 kg Zn/ha, but the lowest in the case of plants fertilized with 0.5 kg Zn/ha. Both indices stress on a high plasticity of maize plants to external supply of zinc.

Components of yield structure. A detailed analysis of maize grain yield components was applied to explain some mechanisms of maize grain yield build-up in response to zinc foliar spray. The main methodology of this procedure implies that maize yield is a resultant of three yield components, namely (i) number of cobs per hectare; (ii) number of kernels per cob (NKC) and (iii) thousand kernels weight (TKW). Relationships between all these yield components were additionally reported for total nitrogen uptake (N_t) and/or nitrogen grain yield (N_{GY}).

In the present study, the number of cob-holding plants, i.e. circa 93 000 per hectare (averaged over three years of study) did not affect the harvested grain yields in any year. Number of kernels per cob (NKC) or per plant, assuming one cob per plant at harvest, is considered as critical yield-component for final grain yield simulation (Rajcan and Tollenaar 1999, Ritchie and Alagarswamy 2003). In analytical procedure, this yield characteristic is worked out with the calculation of two basic yield components, namely the number of rows per cob (NRC) and number of kernels per row (NKR). The first cob characteristic is generally recognized as a highly conservative feature of the developing maize cob, therefore responding poorly to environmental growth factors (Ritche and Alagarswamy 2003). The current field trial fully corroborated the above-presented opinion (Table 2). The second component, NKR, was however considered as the most sensitive element of yield structure to environmental factors (Rajcan and Tollenaar 1999). The NKR values showed, in spite of year-to-year variability, significant response to zinc rates. In comparison to the NPK control treatment, plants fertilized only with 1.0 kg Zn/ha significantly increased the number of kernels per row. This primary component of yield structure showed a significant dependence on total nitrogen uptake (N_t) by maize canopy and on its accumulation in grain yield (N_{GY}). The N_{GY}, as indicated by the R^2 value, was a slightly better index of N supply variability:

$NKR = 0.073N_{GY} + 15.95$,
$R^2 = 0.70$, for $n = 12$ and $P \leq 0.001$

The total number of kernels per cob (NKC) response to zinc foliar application has reflected the observed NKR patterns, following the order of Zn treatments: $0 \leq 0.5 \leq 1.5 < 1.0$. Maize plants fertilized with 1.0 kg Zn/ha produced 17.8% more kernels per cob than those supplied with NPK only. The NKC showed the highest response to N_t and N_{GY} (equal values of R^2) among all studied yield structure components:

$NKC = 1.34N_{GY} + 195.2$,
$R^2 = 0.79$, for $n = 12$ and $P \leq 0.001$

Maize grain yield response to environmental conditions is also frequently expressed by means of cob length (LC), a parameter reflecting the size of two main yield structure components, i.e. number of kernels per cob and their individual size. The analysis of this yield parameter corroborated a high sensitivity of maize to foliar zinc spray, as indicated by the increase in grain yield up to Zn rate of 1.0 kg/ha. This yield structure component showed a slightly higher response to total nitrogen (N_t) uptake by maize canopy than to N_{GY}:

$LC = 0.017N_t + 10.4$,
$R^2 = 0.75$, for $n = 12$ and $P \leq 0.001$

In the case of the third yield structure component, i.e. thousand kernels weight (TKW), the effect of zinc rates was also significant. However, the value of this yield component changed according to treatments, i.e. $0 < 1.0 \leq 0.5 < 1.5$ kg Zn/ha, which opposes to the rank established for the NKC. In addition, this parameter exhibits a slightly stronger dependence on total N status, than on its accumulation in the grain yield:

$TKW = 0.38N_{GY} + 194.5$,
$R^2 = 0.65$, for $n = 12$ and $P \leq 0.001$
$TKW = 0.23N_t + 201.5$,
$R^2 = 0.71$, for $n = 12$ and $P \leq 0.001$

Therefore, it could be concluded that zinc applied to maize leaves at the 5th leaf stage affected the final grain yield in two different ways. The first, major effect is related to the number of kernels per cob, and the second, minor, to the final weight of individual kernels, as expressed by TKW. The cob's length (LC) summarizes the effect of both yield structure components. All reported parameters showed slightly higher dependency to total nitrogen uptake, than to the amount of N in grain yield, as indicated by R^2 values.

The above reported data clearly stress on the conspicuous effect of zinc external supply to maize leaves at early stages on plant growth and grain yield, in spite of a high potential supply of native, i.e. soil zinc (Table 1). Results are in close agreement with those reported by Fecenko and Ložek (1998) for the Czech Republic and by Wrońska et al. (2007) for Poland. In all studied cases an amount of 1.0–1.5 kg zinc per ha applied to maize leaves at the 5–6-leaf stage was sufficient to increase grain yield by circa 1.0 t/ha, on average for each of three consecutive years, highly differing in water supply during maize vegetation. It is necessary to stress that in all series of conducted experiments no symptoms of zinc deficiency were observed. The study reveals also that the yield gap, limited by zinc supply, like in eastern Canada as reported by Subedi and Ma (2009), is a real agronomic problem in maize production under temperate regions of Europe.

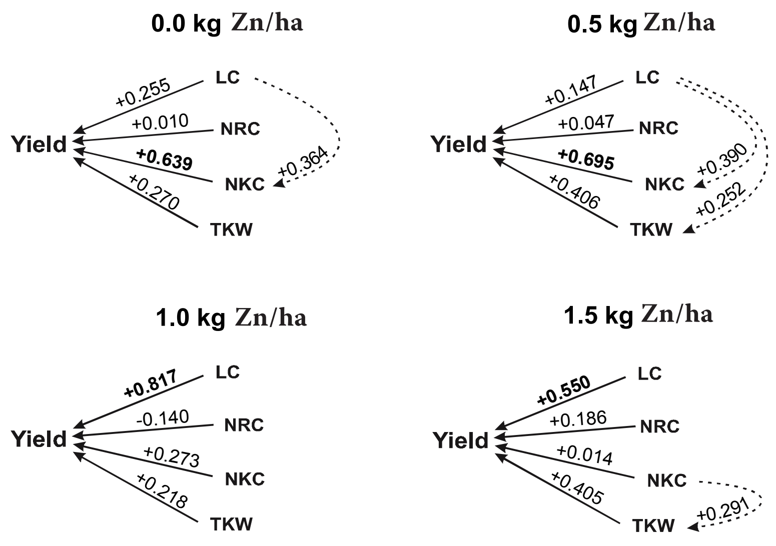
As summarized by Alloway (2004), zinc external supply is a primary factor accelerating plant roots growth and in turn increasing zinc uptake. The second part of this thesis was corroborated by Grzebisz et al. (2008) who found, via applying the growth analysis approach, that maize seedlings treated with zinc fertilizer at the 5th leaf stage accelerated its uptake rate, even being able to double zinc content, as measured at the stage of 7th leaf. As a result, at harvest both dry matter yield and total nitrogen uptake by maize crop increased, but at the same time did not show a uniform distribution among aboveground organs (grain versus straw). The dry matter partitioning is explained by the harvest index (HI) response to foliar zinc application. It showed a declining trend (by a few percentages) in comparison to the NPK-control, irrespective of season-specific growth conditions. The same rule was found for the Nitrogen Harvest Index (NHI). The observed phenomena suggest a seemingly higher response of maize vegetative than reproductive organs to zinc foliar application. However, maize plants receiving an optimal external zinc supply significantly increased grain yield. This specific plants behavior can be explained by enhanced leaf longevity, as induced by an extra N uptake (Rajcan and Tollenaar 1999).

In order to explain the rules of grain yield increase in response to zinc external supply, it is necessary to bring into focus the yield forming role of nitrogen supply to maize plants at early stages of its growth. According to Subedi and Ma (2005), nitrogen supply to maize seedling before the stage of 8th leaf is decisive for establishing the number of ovules as a prerequisite of the number of kernels per plant. Therefore, it can be formulated that maize plants which received 0.5 kg Zn/ha were able to increase the quantity of nitrogen taken up in amounts sufficiently high to affect the number of kernels per plant. However, this amount of extra N accumulation in the plant body is sub-optimal and in turn results in N dilution effect, as presented by high grain yield with simultaneous low protein content. The second mechanism of zinc yield-forming effect was observed in the treatments where the supply of zinc was optimum. It is necessary to exhibit the yield-forming role of nitrogen during flowering and at the beginning of kernel growth. Adequate supply of nitrogen is

Table 4. Coefficients of correlation between grain yield and yield components at different zinc rates ($n = 24$)

Zinc rates (kg/ha)	Length of cob	Number of rows per cob	Number of kernels per cob	Thousand kernel weight
0	0.65***	0.20	0.75***	0.21
0.5	0.81***	0.49*	0.78***	0.50**
1.0	0.82***	0.21	0.14	0.23
1.5	0.84***	0.36	0.85***	0.80***

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$



LC – length of cob
NRC – number of rows per cob
NKC – number of kernels per cob
TKW – tousand kernel weight

Figure 4. Path analysis of relationships between maize grain yield and yield components at different levels of zinc (n = 24)

decisive for the activity of enzymes responsible for the number of starch granules in developing kernels (Cazetta et al. 1999). Therefore, the adequate supply of nitrogen affects the sink capacity of cobs for assimilates during the reproductive period of growth via controlling the potential number of kernels and/or their individual capacity – weight. Maize plant sufficiently supplied with zinc were able to increase both yield of grains and to keep the primary level of total nitrogen content in grains as well, as indicated by the level of grains harvested on the NPK-control plot. Hence, it can be concluded, that zinc applied at early stages of maize growth should be adjusted to the level allowing to increase net N uptake from soil and/or fertilizer sources.

The evaluation of hypotheses reported above was made by applying the path analysis procedure in order to discriminate the specific effect of yield components on harvested yields of maize (Table 4). The number of kernels per cob, as resulted from the analysis of path coefficients was the main factor, which has directly influenced grain yield in 2 of 4 treatments (Figure 4). These two treatments refer to the control plot, i.e. NPK treatment without Zn application, and the one fertilized with the lowest Zn rate, i.e. 0.5 kg Zn/ha. For these two treatments, paths and correlation coefficients were highly significant ($P \leq 0.001$).

In the case of the other two treatments, i.e. those receiving higher zinc rates (1.0 and 1.5 kg/ha), it was found that harvested grain yields were significantly related to the length of cobs (LC). This yield parameter is a very useful index of cob growth, and is in turn related both to the number of kernels per row and also to their individual weight (Elmore and Abendroth 2006). In addition, this cob characteristic reflects fairly well the effect of external conditions on plant growth during the reproductive phase.

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Received on May 14, 2009

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