EFFICIENCY OF MAIZE CULTIVARS FOR ZINC UPTAKE AND USE

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ABSTRACT: Zinc deficiency usually occurs in maize grown in Brazilian acidic soils. The aim of this study was to evaluate commercial maize cultivars for their Zn uptake and utilization efficiency. A greenhouse experiment using nutrient solution with young plants was carried out at Campinas, State of São Paulo, Brazil, in 2002. Treatments consisted of: 0.0; 0.1; 0.2; 0.4 and 0.8 mg L^{-1} Zn in the main plots and 24 commercial maize cultivars in the subplots, in a randomized complete block design. Zn concentration in shoot dry matter (SDM) ranged from 28.4 to 41.6 mg kg^{-1} among cultivars, clearly indicating a dilution effect, since a negative relation between SDM and plant height was shown. Total Zn-shoot content was a good parameter to discriminate cultivars, once correlated with plant height and SDM (r = 0.66** and r = 0.67**, respectively). Analysis of variance and polynomial regression for total Zn-shoot content was highly significant among cultivars and for the interaction cultivar vs Zn-concentration. Plants under low Zn presented up to three-fold differences among efficiency index values (E.I. = 8.59 to 26.42 mg^2 DM μg^{-1} Zn). The results with young plants indicated six maize cultivars classified as Zn-efficient and responsive (AG 7575, Tork, AL Bandeirante, AL 34, AGN 2012, Master) and six cultivars classified as efficient non-responsive (P30F33, P30K75, P30F80, AS 1533, DOW 8420 e AL 30). Other nutrient concentrations in the SDM were within normal limits (K, P, Ca, Mg, Cu, Fe, Mn) for maize young plants.

Key words: *Zea mays* L., Zn-efficiency, Zn uptake, Zn-deficiency, commercial cultivars

EFICIÊNCIA DE CULTIVARES DE MILHO NA ABSORÇÃO E UTILIZAÇÃO DE ZINCO

RESUMO: Nos solos ácidos são comuns os casos de deficiência de zinco (Zn) na cultura do milho. O objetivo do presente trabalho consistiu em avaliar cultivares comerciais de milho quanto à eficiência na absorção e utilização de Zn. O experimento foi conduzido em Campinas, SP, Brasil, 2002, em casa de vegetação com plantas jovens em solução nutritiva, utilizando blocos ao acaso em parcelas divididas, sendo os tratamentos: 0,0; 0,1; 0,2; 0,4 e 0,8 mg L^{-1} de Zn e 24 cultivares comerciais de milho. Os teores de Zn na parte aérea (PA) variaram de 28,4 a 41,6 mg kg^{-1} (1,46 vez) entre as cultivares. O conteúdo total de Zn na PA foi o parâmetro que melhor se correlacionou com a altura de planta (r = 0,66**) e com a matéria seca de parte aérea (MSPA) (r = 0,67**), permitindo diferenciação das cultivares. A análise da variância e a regressão polinomial para essa variável revelaram diferenças significativas entre cultivares, bem como para o índice de eficiência, cujos valores variaram de até três vezes (8,59 a 26,42 mg^2 MS μg^{-1} Zn) em condições de baixo Zn. Os resultados com plantas jovens indicaram seis cultivares como eficientes e responsivas (AG 7575, Tork, AL Bandeirante, AL 34, AGN 2012, Master) e outras seis como eficientes e não-responsivas (P30F33, P30K75, P30F80, AS 1533, DOW 8420 e AL 30). Os teores de K, P, Ca, Mg, Cu, Fe e Mn na MSPA, estiveram dentro dos limites normais para plântulas de milho.

Palavras-chave: *Zea mays* L., absorção de Zn, deficiência de Zn, cultivares comerciais

INTRODUCTION

Acidic low fertility and/or lime-amended high fertility soils frequently present micronutrient deficiencies in annual crops and perennial plantations, specially Zn deficiency in maize, coffee and citrus, which are considered to be highly responsive to Zn fertilization.

Plant demands for Zn vary among species and cultivars. Differential cultivar responses grown under low soil Zn concentrations have been reported in maize, millet, sorghum, rice and wheat, among others (Brown et al., 1972; Clark, 1978; Safaya & Gupta, 1979; Shukla & Raj, 1987; Cakmak et al., 1999; Fageria, 2001). In a study comparing species, Zn uptake efficiency was evaluated in potato, wheat, maize and sunflower assessed by shoot dry matter yields (Trehan & Sharma, 2000), and sunflower plants were found to be the most Zn-efficient.

Root morphology and physiology have been related to genotype ability to overcome Zn deficiency, interfering on the processes of zinc acquisition and release of exudates in the rizosphere (Cakmak et al., 1998; Erenoglu et al., 1999); and also, on differential Zn transport along the vascular system, resulting in variations in Zn distribution and remobilization to vegetative parts and filling grains (Pearson & Rengel, 1995a; 1995b; Pearson et al., 1996a; 1996b; Pearson et al., 1998; 1999).

Maize responses to low Zn in soil and nutrient solution have been evaluated through variations in dry matter yields, tissue mineral composition (Safaya & Gupta, 1979). These authors obtained a significant reduction in total plant dry matter production, due to Zn deficiency, varying from 26.6% to 74%, depending on the cultivar. Kuz-Menko et al. (1994) studied nine maize inbred lines and hybrids for differential Zn uptake and tissue concentration in 14-day-old plants and obtained a high relationship between Zn tissue accumulation at early plant stages and stimulation on ontogeny and dry matter yield. Genotype dry matter yield variation of about 10% was observed and related to tryptophan synthase activity in function of Zn supply to young plants.

Hopkins et al. (1998) compared the quantity of phytosiderophores in the rizosphere of wheat, sorghum and maize under Zn deficiency in nutrient solution and found out that wheat and sorghum roots released higher quantity of exudates as compared to maize. This fact together with the higher maize Zn demand for growth might explain the causes of the prevalence of Zn deficiency in field grown maize as compared to the two other species under the same conditions.

The investigation on germplasm variation for Zn efficiency of several species has stimulated the establishment of plant breeding programs aiming at the selection of plants for this character, once this metal is a highly relevant nutrient for crop yield improvement and also for human nutrition (Cakmak et al., 1999).

The objective of this research was to evaluate commercial maize cultivars for Zn uptake and utilization efficiency using young plants grown in several Zn concentrations.

MATERIAL AND METHODS

The experiment was carried out under greenhouse conditions, at Campinas, SP, Brazil. The experimental design consisted of randomized complete blocks, in split-plots with three replications. Treatments in the main plots were the Zn concentrations (0.0; 0.1; 0.2; 0.4 and 0.8 mg L^{-1}) and in the subplots, 24 maize cultivars currently available in the market.

Seeds were germinated in moistened paper (type Germitest) and seven-day-old seedlings were transplanted to recipients with nutrient solution. The experimental units consisted of 15 L-plastic recipients filled with nutrient solution and an acrylic lid on top with holes (silver painted to avoid light in roots) holding a total of 168 plants per recipient: seven seedlings of each cultivar, inserted in the holes and supported by sponge beads.

The basic nutrient solution consisted of (in mg L^{-1}): Ca 160: K 160; Mg 19.5; N 158 ($N-NO_3$ 138.0 + $N-NH_4$ 20.0); S 64; B = 33; Cl 32.5; P 10.0; Fe 3.6; Mn 0.65; Cu 0.05 and Mo 0.08 (Furlani & Furlani, 1988) (Table 1). The electrical conductivity (E.C.) was 1.51 mS cm^{-1}. Nutrient solution was kept under continuous aeration and the 15 L volume was maintained by daily additions of deonized water. The initial solution pH was adjusted to 5.0 (with 0.1 mol L^{-1} NaOH) and monitored during the experimental period. The solution E.C. was adjusted three times during the experiment by the addition of stock solutions: solution A (stocks 1+5+6) and solution B (stocks 2+3+4) in the same proportions described in Table 1, but 50 fold-concentrated. At 3, 8 and 15 days after transplanting 18.6 mL of each concentrated stock-

Table 1 - Composition of stock solutions used in preparation of the nutrient solution[1].

Stock solution	Salts p.a.	Concentration of stock solution	Proportion of stock in nutrient solution
		g L^{-1}	mL L^{-1}
1	$Ca(NO_3)_2.4H_2O$ / NH_4NO_3	270.0 / 33.8	3.30
2	KCl / K_2SO_4 / KNO_3	18.6 / 44.0 / 24.6	3.60
3	$MgSO_4.7H_2O$	136.9	1.40
4	KH_2PO_4	35.1	8.00
5	$FeSO_4.7H_2O$ / HEDTA	9.16 / 8.68	2.00
6	$MnCl_2.4H_2O$ / Na_2MoO_4. $2H_2O$ / $CuSO_4.5H_2$ / OH_3BO_3	2.34 / 0.26 / 0.20 / 2.04	1.00
7	$ZnSO_4.7H_2O$	43.986	0.0-0.01-0.02-0.04 and 0.08 mL

[1] Furlani & Furlani (1988).

solution A and B was added for each 1 L of nutrient solution and each 0.1 mS cm^{-1} lower than the original value (1.51), in order to maintain similar E.C. in all recipients.

The maximum and minimum air temperature and relative humidity means and mean standard deviations were, respectively: 31.4 ± 2.5°C and 16.4 ± 0.8°C; and 61.7 ± 11.8% and 14.1 ± 5.2%.

Plants were harvested after 17 days, placed in plastic bags and kept in a cooled room for plant height determination. Thereafter, plants were rinsed in distilled water, blotted dry, placed in paper bags and taken to a forced-air oven at 70°C, until constant weight. After this, the following determinations were made: shoot dry matter yield and Zn, P, Ca, K, Mg, B, Fe, Cu and Mn concentrations. Plant samples were oven digested at 450°C and analysed for K by flame-emission photometry; and for the other nutrients by ICP-OES spectrometry. Calculations of Zn-utilization efficiency index (E.I.) for plant shoot dry matter yield were made according to Siddiqi & Glass (1981): EI = shoot DM / [shoot Zn-conc] = $(\text{Shoot DM})^2$ / [total Zn content] = mg^2 DM•mg^{-1} Zn.

Data was submitted to analysis of variance and polynomial regression for all variables. Mean comparisons made by the Duncan test (0.05).

RESULTS AND DISCUSSION

No severe typical visual symptoms of Zn deficiency were observed in the control plants, although they showed a great reduction in shoot height. Zn-deficiency causes internode shortening and decreases leaf size. Chemical analysis of the nutrient solutions in the beggining of the experiment indicated precision for the treatments: 0.00, 0.12, 0.22, 0.44 and 0.86 mg Zn L^{-1} (deonized water and pure salts were used in the preparation of nutrient solutions). Because of the absence of visual Zn symptoms, original seed samples were analyzed for Zn contents and other nutrients in order to verify whether seeds could have supplied seedlings with enough Zn to avoid the appearance of severe deficiency symptoms. A range of 13 to 91 μg Zn g^{-1} expressed in a whole seed dry matter basis was found (average of 25 μg g^{-1}). Bityutskii et al. (1999; 2000; 2002) analyzed metal contents (Ca, Fe, Mn and Zn) of several maize grain parts and found a positive correlation between these metal concentrations and root growth during germination. Mature grains of 25 maize genotypes were classified into groups according to the Fe, Mn and Zn contents in the scutellum. High and low-Zn genotypes were those containing 89-94 and 76 μg Zn g^{-1} scutellum, respectively. In the present experiment, the seed Zn contents determined in the original seed material were expressed in a whole seed basis and the average Zn concentration (25 μg g^{-1}) appeared to be sufficient for the initial seedling supply, since no typical visual symptoms of Zn deficiency were observed.

Dry matter yield varied, in average, 2.43 times among cultivars (from 238 mg to 579 mg per plant). The analysis of variance showed highly significant ($P < 0.01$) differences among cultivars and also a significant interaction among cultivars and Zn rates. The polynomial regression analysis for dry matter production in function of Zn concentrations was significant for cultivars 01, 07, 12, 13, 14, 17 and 20, even though not significant for the others (Table 2; Figure 1).

Plant height varied 1.34-fold, in average, among cultivars (from 58.4 to 78.6 cm). The analysis of variance and polynomial regression revealed highly significant differences among cultivars, as well for the interaction of cultivars and rates of Zn. In fact, the polynomial regression (linear or quadratic) for plant height as a function of Zn was significant only for cultivars 01, 12, 13, 16, 17 and 20. Plant height was apparently a less discriminative parameter than shoot dry matter yield, in response to Zn rates (Table 3).

Once the interaction among cultivars and Zn concentrations was highly significant for dry matter production as well as for plant shoot height, it was necessary to look at each individual plant behavior and to determine the maximum point in the cases there was a quadratic type response. At the highest Zn rates, several cultivars presented reduction in growth, evidencing a higher susceptibility to the metal, while others showed a linear response (Tables 2 and 3). Plant responses in dry matter yield and height clearly indicate that the Zn demand varied among cultivars, and that the Zn concentration in nutrient solution and in plant dry tissue for maximal dry matter yield might be estimated. Since, in this experiment, significant F values for linear or quadratic polinomial regression were obtained for some cultivars (Table 2) individual quadratic equations were found for the cultivars 01, 07, 13, 17 and 20, resulting in the following Zn concentrations

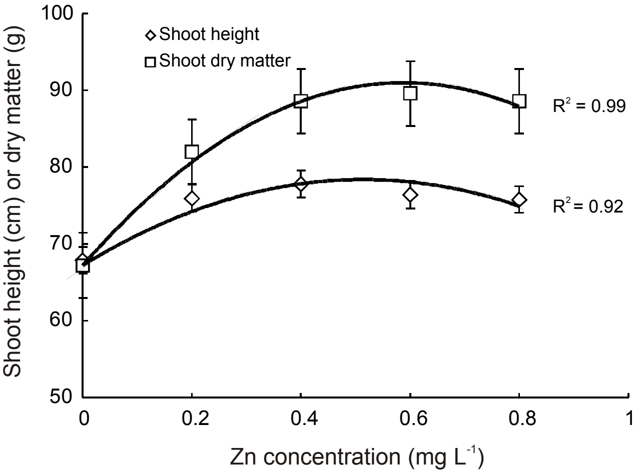

Figure 1 - Shoot height (cm) and shoot dry matter yield (relative scale: g/200 plants) in maize plants grown under increasing Zn concentrations. (Means of 24 cultivars, 72 observations).

Table 2 - Shoot dry matter of 24 day-old maize plants grown under increasing Zn concentrations.

Maize cultivar	Zn concentrations (mg L^{-1})					
	0.0	0.1	0.2	0.4	0.8	Mean
	mg plant $^{-1}$					
10- AL 34 (Var)	438 ab	727 a	606 ab	542 bcd	582 a-e	579
07- AS 1533 (MSH[2])	458 a	543 b	638 a	619 ab	483 a-h	548
06- Tork (SH)	387 a-d	547 b	574 abc	521 b-e	623 abc	530
17- AGN 2012 (DH)	383 a-d	485 bc	515 a-e	586 abc	644 a	523
20- Master (TH)	373 a-e	532 b	485 a-f	532 bcd	618 a-d	508
04- P30F33 (SH)	449 ab	502 b	566 a-d	453 b-h	452 c-i	484
03- P30K75 (SH)	411 a-d	430 bcd	562 a-d	508 b-f	468 b-i	476
09- ALBandeirante (Var[3])	363 a-e	481 bc	568 a-d	493 b -g	476 a-h	476
13- AG 122 (DH)	276 b-e	442 bcd	447 b-g	729 a	490 a-g	476
01- AG 7575 (SH[1])	386 a-d	478 bc	449 b-g	579 abc	436 e-i	466
12- AG 1051 (DH[4])	304 a-e	399 b-e	553 a-d	413 c-j	628 ab	459
11- AL 30 (Var)	378 a-d	450bcd	516 a-e	353 e-j	449 d-i	429
02- P30F80 (SH)	419 abc	416 b-e	430 b-g	488 b-h	377 f-j	426
08- DOW 8420c (MSH)	360 a-e	417 b-e	482 a-f	438 c-i	399 f-j	419
14- Traktor (DH)	269 b-e	380 b-f	354 e-i	437 c-i	510 a-f	390
05- AS 1545 (SH)	298 a-e	373 b-f	394 d-h	373 d-j	391 f-j	365
15- BRS 2223 (DH)	310 a-e	398 b-e	352 e-i	382 d-j	364 f-j	361
21- BRS 3060 (TH)	312 a-e	296 d-g	318 f-i	333 f-j	379 f-j	328
16- BRS 2114 (DH)	245 cde	309 c-g	330 f-i	424 c-j	317 g-j	325
18- XB 8010 (DH)	243 cde	324 c-g	280 ghi	402 d-j	333 f-j	316
24- Exceler (TH)	230 de	211 fg	415 c-h	320 g-j	377 f-j	311
22- AG 6690 (TH)	321 a-e	251 efg	328 f-i	314 hij	311 hij	305
19- AGN 3150 (TH[5])	251 cde	245 efg	209 i	274 ij	237 j	243
23- AGN 3180 (TH)	197 e	198 g	253 hi	248 j	292 ij	238
Means	336	410	443	448	443	

[1]SH = single cross hybrid; [2]MSH = modified SH; [3]Var = variety; [4]DH = double cross hybrid; [5]TH = three-way cross hybrid. Linear polynomial regression (L) and/or quadratic (Q) were significant only for cultivars 01, 07, 12, 13, 14, 17 and 20. Test F (cultivar) = 16.7 **; F interaction (Zn vs cult) = 1.37*; CV% (Zn) = 5.5; CV% (cult) = 22.0. Means followed by the same letters, in columns, do not differ by Duncan's test (0.05).

for maximal dry matter yields: cultivar 01 (AG 7575) – Zn tissue concentration = 38 mg kg^{-1}; maximal dry matter = 523 mg plant^{-1}; cultivar 07 (AS 1533) – 33 and 624; cultivar 13 (AG 122) – 37 and 628; cultivar 17 (AGN 2012) – 47 and 648; and cultivar 20 (Master) – 46 and 616, respectively. These cultivars were more efficient at low Zn concentrations and more susceptible or less tolerant to high Zn. The Zn concentrations for maximal shoot dry matter yield found for cultivars 01, 07, 13, 17 and 20 may be considered an approach for the critical level for deficiency or toxicity. They are very close to the results obtained by Perveen (2000), when comparing bioavailable Zn in soil and plant tissues, using the maize cultivar Azam as a test crop: a critical Zn level was found around 34-35 mg kg^{-1} by graphical and statistical methods.

Nevertheless, some other maize cultivars presented a linear response in shoot dry matter yield as Zn increased in the solution, indicating a higher demand for Zn and higher critical levels: 12 (AG 1051); 13 (AG 122); 14 (Traktor); 16 (BRS 2114); 18 (XB 8010); 23 (AGN 3180); 24 (Exceler), These cultivars were low Zn-efficient and more tolerant to higher Zn concentrations (Table 2).

Shoot-Zn concentrations varied from 28.4 to 41.6 mg kg^{-1} (1.46-fold) among cultivars, but with inversely proportional values in relation to dry matter production and shoot height, indicating a dilution effect. Differences among cultivars were highly significant, but no significant interaction between cultivars and Zn rates was found; Zn concentrations in plant shoot increased as Zn increased in nutrient solution. Polynomial regression was highly significant for all cultivars (Tables 2, 3 and 4). Figure 2 illustrates the relationship for the 24 cultivar means, among shoot Zn-concentrations and the external Zn-concentrations, which was adjusted by a linear equation (R = 0.94**). However, there was a low correlation between shoot-Zn concentrations and shoot dry matter yield (r = - 0.10*) and between shoot-Zn concentrations and shoot height (r = 0.10*) (Table 7).

Table 3 - Shoot height of 24-day-old maize plants grown under increasing Zn concentrations.

Maize cultivar	Zn concentrations (mg L^{-1})					
	0.0	0.1	0.2	0.4	0.8	Mean
	cm					
10- AL 34 (Var)	65.5 a-c	86.5 a	80.8 a	79.3 a	81.0 a-b	78.6
08- DOW 8420c (MSH)	70.7 a	76.2 b-d	77.6 a-c	76.2 a-c	77.4 a-e	75.6
07- AS 1533 (MSH[2])	65.1 a-c	77.0 b	76.8 a-c	78.6 a	77.5 a-e	75.5
06- Tork (SH)	64.7 a-c	76.4 b-d	77.4 a-c	75.6 a-c	82.1 a	75.2
03- P30K75 (SH)	67.9 ab	75.9 b-d	77.8 a-c	76.4 ab	75.8 a-e	74.8
09- ALBandeirante (Var[3])	65.4 a-c	75.7 b-d	79.1 a-b	74.7 a-d	78.7 a-e	74.7
17- AGN 2012 (DH)	65.1 a-c	74.6 b-d	72.9 a-d	75.9 a-c	80.8 a-c	73.9
20- Master (TH)	64.7 a-c	76.7 bc	73.8 a-d	74.2 a-d	79.9 a-d	73.9
04- P30F33 (SH)	67.5 ab	76.3 b-d	77.4 a-c	72.3 a-e	74.3 a-f	73.6
02- P30F80 (SH)	68.2 ab	74.7 b-d	73.9 a-d	76.8 ab	73.7 b-f	73.4
01- AG 7575 (SH[1])	60.5 b-d	74.9 b-d	72.8 b-d	76.7 ab	74.3 a-f	71.9
05- AS 1545 (SH)	66.9 a-c	73.3 b-d	72.6 b-d	71.6 a-e	73.8 b-f	71.6
13- AG 122 (DH)	52.5 ef	74.2 b-d	72.0 b-e	77.6 ab	75.7 a-e	70.4
11- AL 30 (Var)	64.1 a-c	73.6 b-d	74.5 a-d	66.5 e-g	73.0 c-f	70.3
18- XB 8010 (DH)	61.5 b-d	72.6 b-e	67.4 d-g	75.4 a-c	72.0 d-f	69.8
12- AG 1051 (DH[4])	54.1 d-f	68.5 d-f	71.9 b-e	68.5 c-f	77.8 a-e	68.2
16- BRS 2114 (DH)	60.2 b-d	68.8 c-f	70.2 c-f	72.9 a-e	67.2 f-h	67.9
15- BRS 2223 (DH)	60.4 b-d	74.9 b-d	67.4 d-g	67.6 d-f	67.6 f-h	67.6
14- Traktor (DH)	59.2 c-e	71.2 b-e	64.7 e-h	70.2 b-e	72.4 d-f	67.5
21- BRS 3060 (TH)	62.5 bc	65.8 ef	67.9 d-g	67.3 d-f	70.8 e-g	66.9
19- AGN 3150 (TH[5])	61.2 b-d	63.5 fg	59.7 h	66.2 e-g	63.8 gh	62.9
22- AG 6690 (TH)	61.9 bc	61.5 fg	63.0 f-h	61.7 fg	61.8 h	62.0
24- Exceler (TH)	52.6 ef	58.4 g	66.9 d-h	62.6 fg	63.0 h	60.7
23- AGN 3180 (TH)	51.2 f	58.6 g	60.5 gh	59.4 g	62.3 h	58.4
Means	62.3	72.1	71.6	71.8	73.2	

[1]SH = single cross hybrid; [2] MSH = modified SH; [3]Var = variety; [4]DH = double cross hybrid; [5]TH = three-way cross hybrid. Linear polynomial regression (L) and/or Quadratic (Q) were significant only for cultivars 01, 07, 12, 13, 14, 17 and 20. Test F (cultivar) = 24.4**; F interaction (Zn vs cult) = 1.68*; CV% (Zn) = 1.96; CV% (cult) = 5.86. Means followed by the same letters, in columns, do not differ by Duncan's test (0.05).

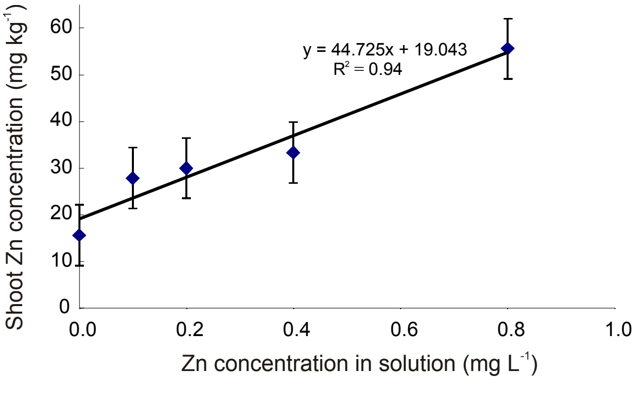

Figure 2 - Shoot Zn concentrations in 24-day-old maize plants grown under increasing Zn concentrations (Means of 24 cultivars, 72 observations).

On the other hand, total Zn-shoot content was the parameter that best correlated with plant height (r = 0.66**) and with dry matter yield (r = 0.67**), better reflecting the differences among genotypes (Tables 5 and 7, Figures 3 and 4). The analysis of variance showed highly significant differences for cultivars and their interaction with Zn concentrations in nutrient solution. The polynomial regression was highly significant for total Zn-shoot content as a function of external Zn concentration, for all cultivars (Table 5). The 24 cultivar means were significantly adjusted for a quadratic polynome (R = 0.97).

The nutrient use efficiency index (EI) for the shoot dry matter production according to Siddiqi & Glass (1981) normally tend to decrease with the nutrient concentration increase in the external media, and this actually occurred to all cultivars in this experiment. This tendency is shown in Figure 5, which refers to the 24 cultivar means. Three-fold differences among cultivars (from 8.59 to 26.42) were obtained for this index in the lowest Zn treatment, clearly demonstrating the differential plant-Zn demands and efficiencies for Zn uptake and use. The

Table 4 - Shoot Zn concentrations of 24-day-old maize plants grown under increasing Zn concentrations.

Maize cultivar	Zn concentrations (mg L^{-1})					
	0.0	0.1	0.2	0.4	0.8	Mean
	mg kg^{1}					
19- AGN 3150 (TH[5])	23.2	40.1	46.2	41.4	57.0	41.6 a
23- AGN 3180 (TH)	24.2	38.3	37.6	45.8	52.1	39.6 ab
22- AG 6690 (TH)	24.6	36.3	37.6	42.5	55.0	39.2 ab
18- XB 8010 (DH)	22.1	35.0	38.9	38.0	59.7	38.7 ab
12- AG 1051 (DH[4])	22.4	31.4	30.6	47.1	57.8	37.8 bc
24- Exceler (TH)	22.3	33.2	28.0	38.6	52.0	34.8 cd
04- P30F33 (SH)	18.8	29.2	28.7	37.7	57.8	34.4 c-e
14- Traktor (DH)	20.3	30.9	31.4	36.0	53.2	34.3 c-f
16- BRS 2114 (DH)	21.8	32.9	34.3	32.7	49.3	34.2 d-f
03- P30K75 (SH)	19.1	28.3	28.6	37.0	56.9	34.0 d-f
21- BRS 3060 (TH)	21.5	28.6	32.3	34.8	50.9	33.6 d-g
11- AL 30 (Var)	19.2	26.0	30.6	37.8	53.3	33.4 d-g
15- BRS 2223 (DH)	20.8	27.4	31.6	34.9	52.0	33.3 d-h
02- P30F80 (SH)	20.4	29.1	30.6	32.2	53.5	33.1 d-h
08- DOW 8420c (MSH)	18.3	25.8	27.8	36.3	55.9	32.8 d-h
01- AG 7575 (SH[1])	15.6	27.8	30.0	33.3	55.6	32.5 d-h
05- AS 1545 (SH)	17.3	26.6	31.2	37.2	49.0	32.3 d-h
13- AG 122 (DH)	20.7	27.4	28.8	32.9	45.5	31.0 d-i
10- AL 34 (Var)	22.5	20.8	26.6	32.7	50.3	30.6 e-i
17- AGN 2012 (DH)	18.0	26.0	28.4	29.9	50.0	30.5 f-i
07- AS 1533 (MSH[2])	17.4	25.4	26.4	33.4	47.7	30.0 ghi
06- Tork (SH)	16.3	26.0	26.7	34.4	45.3	29.7 ghi
09- ALBandeirante (Var[3])	17.7	22.9	25.9	32.7	48.1	29.5 hi
20- Master (TH)	18.6	22.9	26.8	30.5	43.2	28.4 i
Means	15.6	27.8	30.0	33.3	55.6	

[1]SH = single cross hybrid; [2]MSH = modified SH; [3]Var = variety; [4]DH = double cross hybrid; [5]TH = three-way cross hybrid. Linear Polynomial Regression (L) (R=0.97**) significant for all cultivars. Test F (cultivar) = 8.74 **; F interaction (Zn vs cult) = 1.12 ns; CV% (Zn) = 8.22; CV% (cult) = 13.54. Means followed by the same letters in columns do not differ by Duncan's test (0.05).

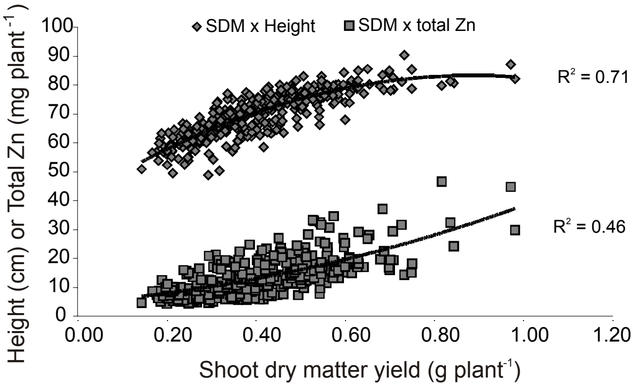

Figure 3 - Relationship between shoot dry matter (SDM) and shoot height (r = 0.81**) (a) and between dry matter and total Zn shoot content (r = 0.67**) (b), for 24-day-old maize plants grown in nutrient solution with five Zn concentrations (total of 360 observations).

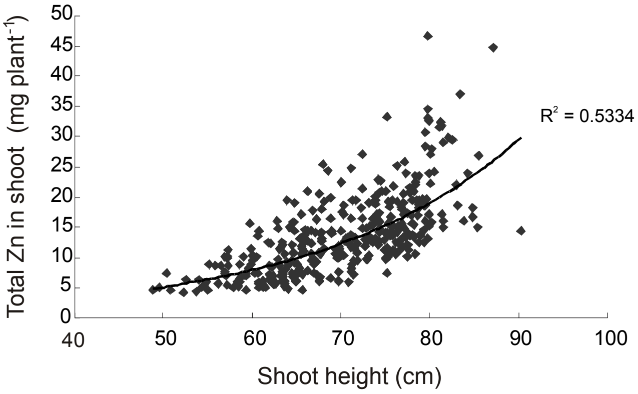

Figure 4 - Relationship between shoot height and total Zn shoot content (simple correlation coefficient, r = 0.66**), for 24-day-old maize plants grown in nutrient solution with five Zn concentrations (total of 360 observations).

Table 5 - Total Zn shoot content in 24-day-old maize plants grown under increasing Zn concentrations.

Maize cultivar	Zn concentrations (mg L^{-1})					
	0.0	0.1	0.2	0.4	0.8	Mean
	mg plant^{-1}					
19- AGN 3150 (TH[5])	5.6 a	9.8 a-d	9.6 bc	11.3 e	13.2 i	9.9
23- AGN 3180 (TH)	4.5 a	7.6 cd	9.4 c	11.3 e	14.7 hi	9.5
12- AG 1051 (DH[4])	6.8 a	12.5 a-d	16.6 a	18.8 a-c	34.3 a	17.8
10- AL 34 (Var)	9.5 a	15.1 a	16.2 a	17.7 a-e	29.0 a-c	17.5
17- AGN 2012 (DH)	6.9 a	12.5 a-d	14.7 a-c	17.6 a-e	31.7 ab	16.7
06- Tork (SH)	6.2 a	14.3 ab	15.3 a-c	17.9 a-d	28.0 b-d	16.4
03- P30K75 (SH)	7.8 a	12.2 a-d	16.0 ab	18.7 a-c	26.4 b-d	16.2
04- P30F33 (SH)	8.5 a	14.6 ab	16.2 a	16.8 a-e	25.0 c-e	16.2
07- AS 1533 (MSH[2])	7.9 a	13.8 a-c	16.7 a	20.2 ab	22.3 d-g	16.2
13- AG 122 (DH)	5.6 a	11.9 a-d	12.8 a-c	22.8 a	22.3 d-g	15.1
01- AG 7575 (SH[1])	6.0 a	13.2 a-d	13.5 a-c	18.9 a-c	23.1 c-f	15.0
20- Master (TH)	6.8 a	12.2 a-d	12.7 a-c	16.3 b-e	26.1 b-d	14.8
11- AL 30 (Var)	7.3 a	11.7 a-d	15.8 a-c	13.2 c-e	23.6 c-f	14.3
14- Traktor (DH)	5.4 a	11.4 a-d	11.1 a-c	15.6 b-e	27.7 b-d	14.2
09- ALBandeirante (Var[3])	6.4 a	10.8 a-d	14.5 a-c	16.1 b-e	22.7 d-g	14.1
02- P30F80 (SH)	8.4 a	12.0 a-d	13.1 a-c	15.5 b-e	19.8 e-h	13.8
08- DOW 8420c (MSH)	6.6 a	10.6 a-d	13.3 a-c	15.8 b-e	22.4 d-g	13.8
18- XB 8010 (DH)	5.3 a	10.9 a-d	10.8 a-c	15.3 b-e	19.7 e-h	12.4
05- AS 1545 (SH)	5.2 a	9.9 a-d	12.3 a-c	13.9 b-e	19.0 e-i	12.0
15- BRS 2223 (DH)	6.3 a	11.0 a-d	11.1 a-c	12.8 c-e	18.8 e-i	12.0
22- AG 6690 (TH)	7.6 a	8.8 a-d	12.2 a-c	13.3 c-e	16.7 g-i	11.7
21- BRS 3060 (TH)	6.7 a	8.4 b-d	10.2 a-c	11.7 de	18.6 f-i	11.1
16- BRS 2114 (DH)	5.3 a	9.9 a-d	11.2 a-c	13.5 c-e	15.3 hi	11.0
24- Exceler (TH)	5.0 a	7.0 d	11.1 a-c	12.0 de	18.6 f-i	10.8
Means	6.6	11.3	13.2	15.7	22.5	

[1]SH = single cross hybrid; [2]MSH = modified SH; [3]Var = variety; [4]DH = double cross hybrid; [5]TH = three-way cross hybrid. Linear Polynomial Regression (L) presented significant (R**) for all cultivars. Test F (cultivar) = 8.42 **; F interaction (Zn vs cult) = 1.42*; CV% (Zn) = 5.69; CV% (cult) = 23.46. Means followed by the same letters, in columns, do not differ by Duncan's test (0.05).

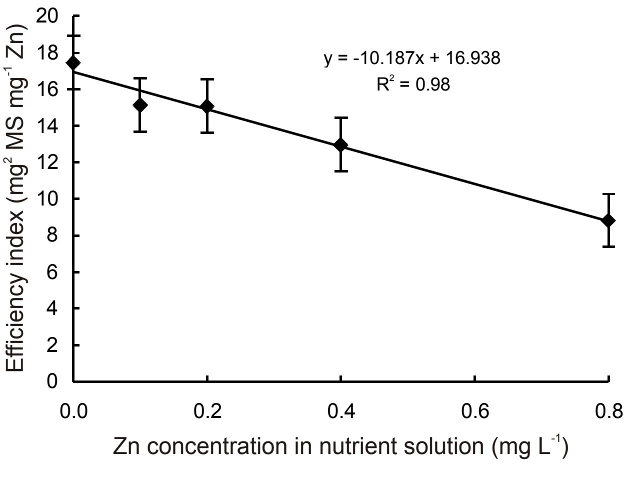

Figure 5 - Efficiency index in maize plants (dry matter yield per unity of Zn shoot concentration) as a function of Zn concentrations in solution. Means over 24 cultivars (72 observations).

efficiency index variation was probably influenced by differential maize cultivar abilities in using Zn for germination and growth, once no correlation was found between seed Zn concentration and EI in the free-Zn treatment. Additionally, they were not apparently related to the crossing-type material (simple hybrid, double or three-way cross, or variety).

Genotypes may present different mechanisms for Zn efficiency. Welch (1999) emphasized the importance of Zn grain reserves on early wheat seedling performance, mainly under low external Zn conditions and that the benefits of Zn grain reserves conferring seedling vigor during germination cannot be substituted by Zn supply after germination. Greater Zn grain reserves resulted in greater seedling root and shoot growth in a Zn deficient soil and the differences between plants from high-Zn and low-Zn-grains were evident even after six weeks of growth (Welch, 1999). Nevertheless, despite showing the same tissue or grain Zn concentrations, efficient cultivars may differ from inefficient ones by their ability of expressing Zn-efficiency, only at low Zn levels, by maintaining physiological processes and higher enzyme activities (carbonic anhydrase and others). At sufficient Zn levels, differences in enzyme activities between Zn-efficient and Zn-inefficient cultivars may not appear (Rengel, 1999).

In order to evaluate and classify the cultivars as to their efficiency in Zn uptake and use under low Zn and to their responsiveness to Zn supply, values of efficiency index (EI) at low Zn were plotted against the relative increases in dry matter production, that is, the ratio of maximum/minimum dry matter yield (DMmax/DMmin) (Figure 6). The overall mean for the 24 cultivars, in each axis, allowed to classify them in: *efficient-responsive* (ER) = 01 (AG 7575); 06 (Tork); 09 (AL-Bandeirante); 10 (AL 34); 17 (AGN 2012); 20 (Master); *efficient-non-responsive* (ENR) = 02 (P30F80); 03 (F30K75); 04 (P30F33); 07 (AS 1533); 08 (DOW 8420); 11 (AL 30); *inefficient-responsive* (IR) = 12 (AG 1051); 13 (AG 122); 14 (Traktor); 16 (BRS 2114); 18 (XB 8010); 23 (AGN 3180); 24 (Exceler); and *inefficient-non-responsive* (INR) = 05 (AS 1545); 15 (BRS 2223); 19 (AGN 3150); 21 (BRS 3060); 22 (AG 6690). Therefore, twelve cultivars were considered efficient, with EI values above the average (17.5 mg^2 DM mg^{-1} Zn) and twelve were inefficient. Responsive cultivars presented relative increases in dry matter production above de average (DMmax/DMmin ratio > 1.53) (Figure 6).

Nutrient concentrations (K, P, Ca, Mg, Cu, Fe and Mn) in plant shoot were within normal limits (Table 6) for young maize plants. Zn concentrations in plants were positively correlated with K (r = 0.27**) and Ca (r = 0.25**), that is, there was a tendency to increase the K and Ca concentrations in plants in function of Zn con-

Table 6 - Shoot K, P, Ca, Mg, Cu, Fe and Mn concentrations of 24-day-old maize plants grown under increasing Zn concentrations (means over 72 observations and 24 cultivars).

Nutrient	Zn concentrations (mg L^{-1})					
	0.0	0.1	0.2	0.4	0.8	Mean
K (g kg^{-1}) (1)	50.6	51.2	51.7	52.3	52.0	51.5
P (g kg^{-1}) (2)	6.4	5.4	4.9	4.7	4.8	5.2
Ca (g kg^{-1}) (3)	16.0	17.0	18.7	17.8	18.2	15.3
Mg (g kg^{-1}) (4)	5.2	5.6	5.2	5.3	4.3	4.8
Cu (mg kg^{-1}) (5)	12.8	11.6	10.6	9.4	9.9	10.9
Fe (mg kg^{-1}) (6)	235.1	171.7	159.0	152.0	140.5	171.6
Mn (mg kg^{-1}) (7)	143.5	127.5	117.4	111.6	124.9	125.0

[1]Polynomial Regression not significant for all cultivars. Test F (cultivar) = 8.69 **; F interaction (Zn vs cult) = 1.02ns; CV% (Zn) = 7.12; CV% (cult) = 6.93. [2]Polynomial Regression not significant for all cultivars. Test F (Zn) = 6.03*. Test F (cultivar) = 11.45**; F interaction (Zn vs cult) = 1.59**; CV% (Zn) = 9.70; CV% (cult) = 12.35. [3]Polynomial Regression for Zn levels not significant for all cultivars. Test F (Zn) = 4.88*. Test F (cultivar) = 20.49**; F interaction (Zn vs cult) = 1.59**; CV% (Zn) = 4.09; CV% (cult) = 8.96. [4]Polynomial Regression for Zn levels not significant for all cultivars. Test F (Zn) = 18.59**. Test F (cultivar) = 10.21**; F interaction (Zn vs cult) = 0.92ns; CV% (Zn) =2.13; CV% (cult) = 9.84. [5]Polynomial Regression not significant for all cultivars. Test F (Zn) = 10.53**. Test F (cultivar) = 8.69**; F interaction (Zn vs cult) = 1.51**; CV% (Zn) = 7.26; CV% (cult) = 12.94. [6]Quadratic Polynomial Regression (R*) for cultivars 1, 10, 13, 14, 16, 17, 20, 21 and 22. Test F (cultivar) = 3.65**; F interaction (Zn vs cult) = 1.88**; CV% (Zn) = 5.78; CV% (cult) = 13.77. [7]Quadratic Polynomial Regression (R*) for cultivar means. Test F (Zn) = 16.67**. Test F (cultivar) = 14.42**; F interaction (Zn vs cult) = 1.14ns; CV% (Zn) = 7.25; CV% (cult) = 11.25.

Table 7 - Simple correlations (r) between the variables evaluated in 24-day-old maize plants grown under increasing Zn concentrations (pairs of 360 observations).

	Height	TotZn	Zn	K	P	Ca	Mg	Cu	Fe	Mn
SDM	0.81**	0.67**	-0.10*	-0.43**	-0.70**	ns	0.41**	-0.28**	-0.45**	-0.34**
Height	---	0.66**	0.10*	-0.29**	-0.69**	ns	0.46**	-0.35**	-0.58**	-0.27**
Zn	---	---	---	0.27**	-0.11*	0.25**	-0.37**	-0.24**	-0.40**	ns
K	---	---	---	---	0.38**	ns	-0.29**	ns	ns	ns
P	---	---	---	---	---	ns	-0.30**	0.53**	0.65**	0.58**
Ca	---	---	---	---	---	---	0.18**	ns	ns	0.40**
Mg	---	---	---	---	---	---	---	0.12*	ns	0.14**
Cu	---	---	---	---	---	---	---	---	0.67**	0.61**
Fe	---	---	---	---	---	---	---	---	---	0.55**

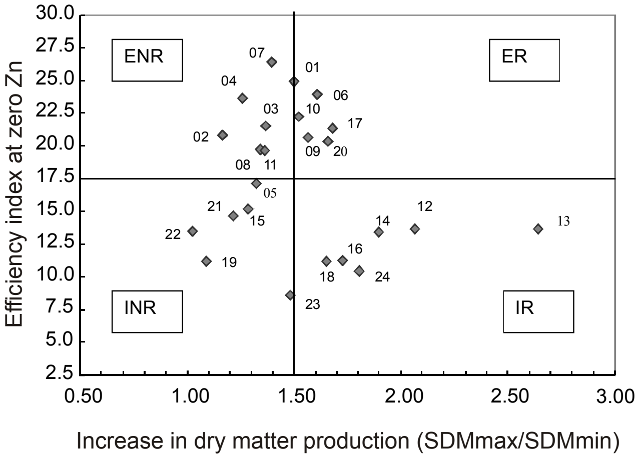

Figure 6 - Classification of maize cultivars: y-axis = efficiency index (mg^2 DM mg^{-1} Zn) for Zn utilization at the lowest Zn rate in solution (0.0 mg L^{-1}); x-axis = relative increase in shoot dry matter (SDM) in response to Zn rates (SDM maximum/minimum): Efficient -Responsive (ER) = 01 (AG 7575), 06 (Tork), 09 (AL Bandeirante), 10 (AL 34), 17 (AGN 2012) and 20 (Master); Efficient-non-Responsive (ENR) = 02 (P30F80), 03 (P30K75), 04 (P30F33), 07 (AS 1533), 08 (DOW 8420) and 11 (AL 30); Inefficient-Responsive (IR) = 12 (AG 1051), 13 (AG 122), 14 (Traktor), 16 (BRS 2114), 18 (XB 8010), 23 (AGN 3180) and 24 (Exceler); and Inefficient-non-responsive (INR) = 05 (AS 1545), 15 (BRS 2223), 19 (AGN 3150), 21 (BRS 3060) and 22 (AG 6690).

centration in the external media and Zn concentration in plants. These positive correlations might be due to beneficial effect of Zn to roots increasing the uptake of those nutrients. In contrast, Zn concentration in plants demonstrated a negative correlation with P (r = - 0.11*), Mg (r = - 0.37**), Cu (r = - 0.24**) and Fe (r = - 0.40**) contents in plants. There was a tendency to decrease shoot P, Mg, Cu and Fe concentrations with increasing external Zn and Zn plant contents. In the case of P, this negative correlation might be due to the formation of insoluble zinc phosphate in the rhizosphere. Nevertheless, for Mg, Cu and Fe there was a higher competition with Zn for sites of uptake by roots, what became more evident with the Zn increase in the nutrient solution (Tables 6 and 7). The competition among bivalent cations for the carrier binding sites in the plasma membrane is well documented (Marschner, 1995) and usually when the external concentration of one of them increases, a significant reduction in the concentration of other bivalent cations in plant tissue is observed.

Differences among cultivars were small, although significant, for K (46.4 - 57.8 g kg^{-1}); P (4.0 - 6.2 g kg^{-1}); Ca (11.7 - 17.7 g kg^{-1}); Mg (3.9 - 5.5 g kg^{-1}); Cu (8.3 - 12.6 mg kg^{-1}); and Fe contents (152 - 191 mg kg^{-1}), considering that all materials were submitted to the same concentrations of these nutrients (F test significant for cultivars, Table 7). The variation in nutrient concentrations among the cultivars could be due to a dilution effect related to higher or lower dry matter yield. This is evidenced by the significant negative correlations between shoot dry matter yield and contents of K, P, Cu, Fe and Mn; and also betwe-en plant height and these nutrient concentrations (Table 6).

The technique used for the evaluation of young plants in nutrient solution allowed differentiating maize cultivars as to their efficiency in Zn uptake and use. The genotype responses were evaluated in 24-day-old plants for their dry matter yields, plant heights and total Zn contents in shoot parts. Twelve out of 24 cultivars were efficient at low Zn rates and six of them were responsive to increasing Zn supply in nutrient solution. Grain reserves were apparently enough to provide Zn for good germination and initial seedling growth. However, the variation in Zn efficiencies observed among cultivars might be attributed to differential physiological mechanisms, conferring abilities in utilizing Zn for germination and initial seedling growth that show up especially under Zn-deficiency, characterizing plant adaptation to low Zn levels.

Cultivars presenting higher relative dry matter increases (DMmax/DMmin) in response to Zn supply presented also low Zn-efficiency indexes (Zn-inefficient-responsive cultivars: 12=AG 1051, 13= AG 122; 14 = Traktor, 24= Exceler), evidencing to be high Zn demander plants.

Corn cultivars have been extensively tested in the State of São Paulo during several years (Duarte & Paterniani, 2000a). Cultivars AG 1051, AG 122; Traktor and Exceler are well-adapted and high yielding cultivars. Exceler, a highly Al-susceptible cultivar, has shown good field performance in acid soils, what probably indicated P-efficiency characters. The Zn-inefficient-non-responsive cultivars 19 (AGN 3150) and 23 (AGN 3180) have presented good potential yielding only in restricted areas. Among the Zn-efficient cultivars AGN 2012 has shown an expressive behavior and scored in 8th out of 24 top materials. Tork and Master (Zn-efficient-responsive cultivars) are high yielding genotypes in acid soils (around 8,000 and 8,500 kg ha^{-1}, respectively), but Al-susceptible genotypes, and the latter also show high yield stability in the whole State. P30K75 and P30F33 (Zn-efficient-non-responsive cultivars) performed better in acid soils than in non-acid ones (P30F33 had 20% higher yield - average of 8,596 kg ha^{-1} - in acid as compared to non-acid soils), evidencing highly adapted genotypes (Duarte & Paterniani, 2000b).

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