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Corn nutrition and yield as a function of boron rates and zinc fertilization

Avaliação nutricional e produtividade do milho em função de doses de boro e adubação com zinco

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Abstract

Brazilian Cerrado soils are commonly deficient in boron (B) and zinc (Zn). It is still debated whether B and Zn interaction has a synergistic or antagonistic effect on the absorption thereof. Thus, we conducted this study to evaluate the effect of boron rates (0, 1, 2, 3, and 4 kg ha^{-1}, as boric acid), with or without zinc fertilization (2 kg ha^{-1} Zn, as zinc sulfate), on corn nutritional status and grain yield. We also assessed the residual effect of such fertilization on the fall corn crop grown on an Oxisol in a no-tillage system. A synergistic effect between B and Zn was observed on corn nutritional status when applied to the soil at rates of up to 2 kg ha^{-1}, with higher soil contents resulting from the interaction between these micronutrients. Zinc fertilization and increasing boron rates had no significant influence on corn grain yield in both spring/summer and fall crops, grown on a boron-deficient, clayey soil of Cerrado biome.
Key words: Borated fertilizer. Boric acid. Micronutrients. Nutrient concentrations. *Zea mays* L.

Resumo

Solos do Cerrado Brasileiro são comumente deficientes em boro (B) e zinco (Zn). Muito se discute a respeito da interação entre B e Zn, em função de um possível efeito sinérgico ou antagônico na absorção desses nutrientes, desta forma o objetivo com este estudo foi avaliar o efeito das doses de boro. (0, 1, 2, 3, e 4 kg ha^{-1}, na forma de ácido bórico), com ou sem adubação com zinco (2 kg ha^{-1} Zn, na forma de sulfato de zinco), avaliando o estado nutricional e a produtividade de grãos de milho, além do efeito residual desta adubação no solo no cultivo de milho subsequente, em um Latossolo Vermelho distrófico em plantio direto. Houve efeito sinérgico no estado nutricional do milho entre B e Zn aplicado ao solo em doses de até 2 kg ha^{-1}, com maiores concentrações no solo decorrentes da interação desses micronutrientes. A adubação com zinco e as doses crescentes de boro não influenciaram significativamente a produtividade de grãos de milho primavera/ verão e outono em um solo argiloso com deficiência de boro em condições de Cerrado.
Palavras-chave: Fertilização borratada. Ácido bórico. Micronutrientes. Concentração de nutrientes. *Zea mays* L.

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Introduction

A proper nutrient supply (amount, source, method, and time) is fundamental to improve corn growth and yield. Some strategies can be used to achieve high and profitable corn yields such as seeding at optimal time and growing suitable genotypes for each region, as well as ensuring proper nutrient balance and supply (GALINDO et al., 2016).

Under tropical conditions, micronutrient deficiencies of boron (B) and zinc (Zn) are major problem in corn farming. These deficiencies are mainly caused by soil low fertility, e.g. in the Cerrado biome (savannah), nutrient harvest exports, high-level phosphate application, and non-incorporated limestone in no-tillage systems (overliming), which increases Zn insolubilization. For these reasons, Zn shows the highest grain-yield responses in corn crops in Brazilian soils.

Zinc is one of the most important micronutrients for growth and development of higher plants. This nutrient is involved in several vital physiological processes such as protein synthesis, energy production, and membrane integrity maintenance (HANSCH; MENDEL, 2009; DRISSI et al., 2017). Among its basic functions in plants, Zn compounds many enzymes such as dehydrogenases, proteinases, peptidases, and phosphohydrolases, besides being related to carbohydrate, protein, and phosphate metabolism and auxin, RNA, and, ribosome formation (MARSCHNER, 2012; OJEDA-BARRIOS et al., 2014). Moreover, it is involved in phenol metabolism, starch formation, cell growth and multiplication, and pollen fertility (MARSCHNER, 2012; DAVARPANAH et al., 2016). Therefore, since corn plants are sensitive to Zn deficiency (GUPTA et al., 2008; DRISSI et al., 2017), it has become a worldwide constraint in such crops (CAKMAK, 2008).

Likewise, B is also related to several plant physiological processes such as sugar transport, cell wall synthesis, lignification, cell wall structuring, carbohydrate metabolism, RNA metabolism, respiration, indole acetic acid (IAA) metabolism, phenol metabolism, ascorbate metabolism, and plasma membrane integrity (BELL; DELL, 2008; SONGKHUM et al., 2018), as well as pollen grain germination and tube elongation. Also, this element is indirectly responsible for activation of dehydrogenase enzymes, sugar translocation, nucleic acids, and plant hormones (EL-SHEIKH et al., 2007; MARSCHNER, 2012).

Hosseini et al. (2007) proved significant effects of B × Zn interaction on many plant biochemical and physiological processes. Nutritional interactions interfere with plant mineral composition, whereby an excess of one element can stimulate or inhibit absorption of others. Such relationships vary widely and can occur inside the cells or in the rhizosphere (MENGEL; KIRKBY, 2001). Both B and Zn are essential to improve ATPase functioning, which is essential for the use of metabolic energy (ATP). Furthermore, the absence of B may reduce Zn efficiency in plants and vice-versa (DAVARPANAH et al., 2016; SONGKHUM et al., 2018).

According to Tavallali (2017), adverse effects of B deficiency and toxicity in pistachio (*Pistacia vera* L. cv. Badami) seedlings are alleviated by increasing Zn levels up to 10 mg kg^{-1} soil. Also, at proper concentrations, B and Zn interact synergistically. Understanding when this happens may provide relevant results and hence increase plant growth and productivity. In this line of thought, the residual effect of B and Zn fertilization on fall corn crops should also be investigated. Besides that, new corn hybrids are usually more productive and nutrient-demanding, so there is also a need to investigate these modern hybrids.

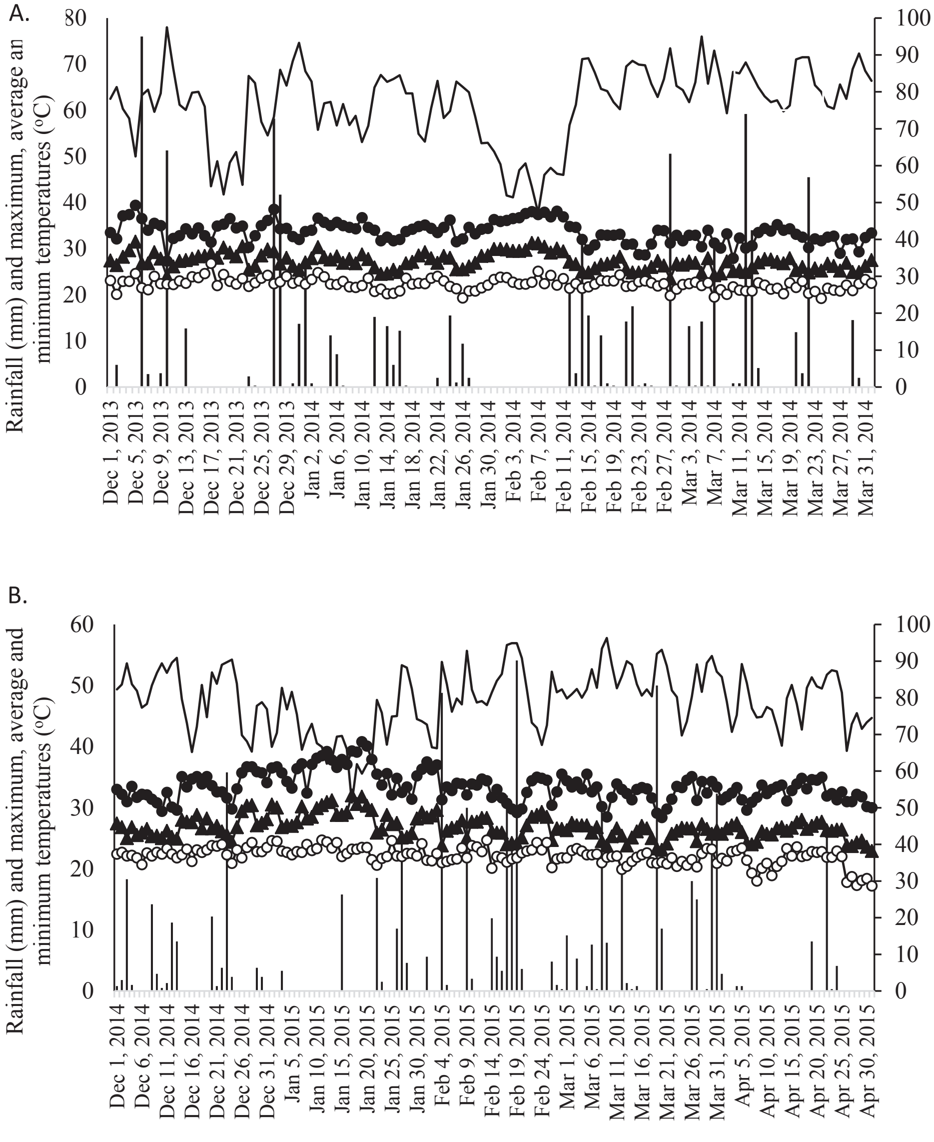
In Brazilian Cerrado soils, B and Zn deficiencies are common, mainly where high levels of phosphorus have been applied, which leads to Zn deficiency. Moreover, it is still debated whether B and Zn interaction has a synergistic or antagonistic effect on their respective absorption from the soil. Thus, this study aimed to evaluate the effect of B fertilization, with or without Zn, on corn nutritional status and grain yield during the spring season, in addition to the residual effect of such fertilizations on fall corn crop grown on a boron-deficient soil of Cerrado biome.

Materials and Methods

Geographical location and management history

Spring-summer and fall corn crops were grown in the same experimental area, which belongs to the Faculty of Engineering at UNESP, located in Selvíria-MS, Brazil. The area is at an altitude of 335 m above sea level, and average annual temperature, rainfall, and humidity are 23.5 ºC, 1,370 mm, and 70-80%, respectively. The soil is classified as a dystrophic red Latosol "*Latossolo Vermelho Distrófico*" with clayey texture (Oxisol), according to Embrapa (2013). The area has been grown with annual crops for over 27 years, of which the last eight years have been under no-tillage system with the last year of fallow. Figure 1 shows the climatic conditions during both experiments of spring-summer and fall corn crops.

Figure 1. Rainfall, air relative humidity and maximum, average and minimum temperatures obtained from the weather station located in the Education and Research Farm of FE / UNESP during the maize cultivation in the period December 2013 to April 2014 (A) and December 2014 to April 2015 (B).



Experimental design

A randomized block experimental design with four replications was adopted, under a 2 × 5 factorial arrangement, consisting of application (or lack thereof) of 2 kg ha^{-1} Zn (in the form of zinc sulfate) and five B rates (0, 1, 2, 3, and 4 kg ha^{-1}, in the form of boric acid). Treatments were applied to the soil at seeding and about 0.10 m apart from corn rows. Plots were 5-m long with six rows spaced 0.45 m apart. The useful area of plots consisted of the four central rows, excluding 0.5 m from the edges.

Trial establishment and management

The soil chemical attributes in the arable layer (0-0.20 m) were determined before the experiment, following the method proposed by Raij et al. (2001) (Table 1). Based on this soil analysis and corn requirements, all the treatments were fertilized at planting with 400 kg ha^{-1} of the 08-28-16 formula, which corresponded to 32, 112, and 64 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. In both seasons, corn crops were conducted under no-tillage system.

Table 1. Soil chemical attributes in 0-0.20 m layer, before the implementation of the experiment.

Soil chemical attributes	0-0.20 m layer
P (resin)	10 mg dm^{-3}
S (SO_4)	5 mg dm^{-3}
Organic matter	22 g dm^{-3}
pH ($CaCl_2$)	5.3
K	2.4 mmol$_c$ dm^{-3}
Ca	21.0 mmol$_c$ dm^{-3}
Mg	18.0 mmol$_c$ dm^{-3}
H+Al	28.0 mmol$_c$ dm^{-3}
B (hot water)	0.16 mg dm^{-3}
Cu (DTPA)	3.2 mg dm^{-3}
Fe (DTPA)	22.0 mg dm^{-3}
Mn (DTPA)	24.2 mg dm^{-3}
Zn (DTPA)	1.2 mg dm^{-3}
Cation exchange capacity (pH 7.0)	69.4 mmol$_c$ dm^{-3}
Base saturation (%)	60

Both seasons were seeded with corn hybrid DKB 350 PRO (armyworm [*Spodoptera frugiperda*] resistant), using a shank-type seeder. Sowings were carried out on 12/04/13 and 04/15/14 by depositing 73,333 seeds ha^{-1}. Plantlets emerged five days after seeding. Soil B and Zn applications were also performed manually on 12/04/13.

The herbicides tembotrione (84 g ha^{-1} active ingredient [a.i.]) and atrazine (1,000 g ha^{-1} a.i.) were applied at V2 corn stage (two fully expanded leaves), plus vegetable oil (720 g ha^{-1} a.i.) as adjuvant. Neither pest nor disease management was necessary in either seasons. At V6 stage, nitrogen topdressing was performed (100 kg N ha^{-1}) by broadcasting urea in between corn rows, without soil incorporation. Whenever necessary and after nitrogen fertilization, sprinkler irrigation was done, using a water depth of 13 mm, from a center pivot system.

Corn hybrid, crop management, sowing fertilization, and nitrogen topdressing were the same in both spring-summer and fall crops of 2014. However, the residual effect of soil treatments (B rates, with or without Zn) were evaluated, i.e., fall crop treatments were superimposed on the previous crop ones. Spring-summer and fall corn were harvested 112 and 122 days after plant emergence, respectively.

Data collection

For both corn crops, leaf concentrations of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn were determined as proposed by Malavolta et al. (1997). It consisted of collecting the middle third of 20 leaves of the main ear at female flowering, per plot, according to the method described by Cantarella et al. (1997). Grain yield was measured using ears from plants within the useful plot area. After mechanical threshing, grains were weighted, and data were transformed into kg ha^{-1} at 13% moisture. After harvesting both crops, B and Zn contents in the soil (0-0.20 m layer) were also analyzed using a soil auger, and sampling was carried out at five points per plot, where both elements had been applied.

Statistical analysis

Data were submitted to analysis of variance (F-test). When significant ($p \leq 0.01$ and $p \leq 0.05$), means were compared by the Tukey´s test ($p \leq 0.05$) for Zn application (with or without) and adjusted to polynomial regression models for B rates, using the SISVAR software (FERREIRA, 2011).

Results and Discussion

Leaf macronutrient concentrations

Leaf macronutrient concentrations of spring-summer corn were not influenced by B rates or Zn fertilization applied to the soil (Table 2). Of these nutrients, only S was influenced by Zn fertilization, with higher values, likely because the applied source was zinc sulfate (Table 2). Jamami et al. (2006) evaluated different Zn rates applied to the soil and did not observe an effect on leaf macronutrient concentrations in corn. Conversely, Adiloglu and Adiloglu (2006) assessed the effect of increasing B rates (0, 10, and 20 mg kg^{-1}) and Zn (0 and 10 mg kg^{-1}) on corn grown in a Zn-deficient soil; they found that the concentrations of N, P, and K in plants increased with B and Zn applications.

When compared to no application, Zn showed a residual effect in fall corn only on N leaf concentration (Table 3). Such a high concentration might have occurred due to the equilibrium between mineral and protein N, and the role of Zn in processes where N is essential such as enzyme activation, protein synthesis, and cell division (MANZEKE et al., 2014; DRISSI et al., 2017). However, if protein synthesis was reduced, N concentration could remain the same since N-NO_3^- or N-NH_4^+ would show higher concentrations.

Regarding the residual effect of B rates on fall corn, no isolated effect was observed on macronutrient concentrations (Table 3). Yet, when B fertilization was associated with Zn application, leaf Ca and Mg concentrations increased up to B rates of 1.51 and 1.20 kg ha^{-1}, respectively (Figures 2A, B). According to Marschner (2012), the concentrations of Ca and B are correlated in plant tissues, which might explain B nutrition status of plants in the present study. Despite adequate Ca supply in roots, this element could not be effectively used in the absence of B (SHAMS et al., 2012). Boron enabled plants to absorb more Ca in a given time or use it more efficiently in their metabolism after absorbed (GANMORE-NEUMANN; DAVIDOV, 1993). Boron deficiency inhibits Ca translocation and induces abnormal changes in its metabolism in the cell wall (YAMAUCHI et al., 1986). Root elongation also depends on cell turgor pressure and hence, on the stability of the cell wall (SHAMS et al., 2012). Both B and Ca are required for the stability of the pectin fraction in cell walls (KOBAYASHI et al., 1999).

Table 2. Leaf concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) of spring/summer corn, affected by boron rates applied to the soil, with and without fertilization with zinc in the soil. Selvíria - MS, Brazil.

	N	P	K	Ca	Mg	S
	---------------------------------------(g kg^{-1})---------------------------------------					
With zinc	27.08 a	3.42 a	27.06 a	3.86 a	1.69 a	2.20 a
Without zinc	27.28 a	3.52 a	26.17 a	4.15 a	1.79 a	1.88 b
H.S.D. (5%)	1.79	0.20	1.40	0.57	0.30	0.03
B rates (kg ha^{-1})						
0	28.48	3.43	26.35	4.05	1.77	2.03
1	27.45	3.52	26.23	4.15	1.80	2.03
2	26.48	3.50	26.18	3.90	1.75	2.08
3	26.60	3.47	26.71	4.13	1.85	2.02
4	26.88	3.43	27.60	3.80	1.55	2.03
Overall mean	27.18	3.47	26.62	4.00	1.74	2.04
C.V. (%)	8.61	7.41	6.88	17.48	22.52	19.37

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

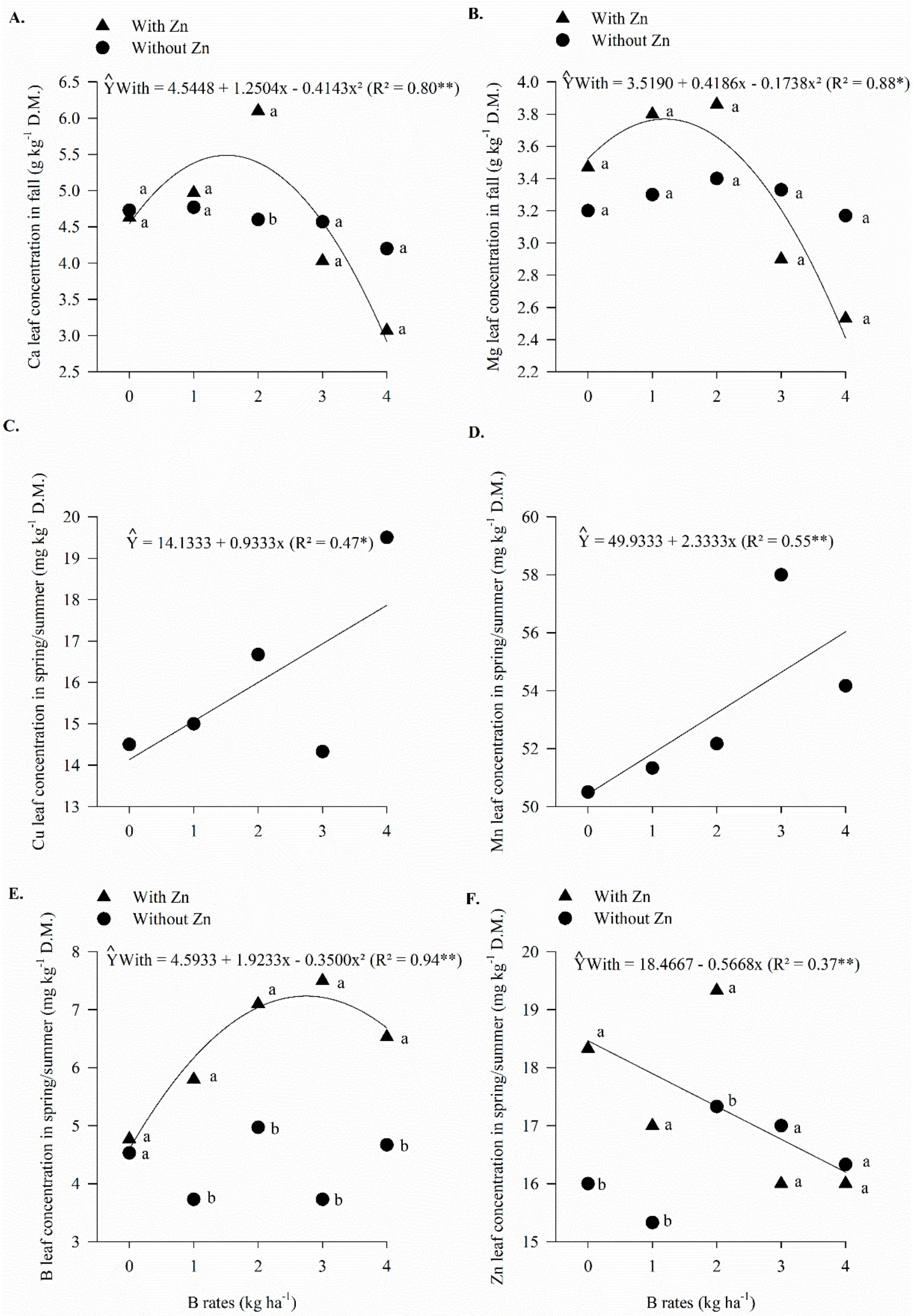
Table 3. Leaf concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) of fall corn, affected by residual of boron rates applied to the soil, with and without fertilization with zinc in the soil. Selvíria - MS, Brazil.

	N	P	K	Ca	Mg	S
	---------------------------------------(g kg^{-1})--					
With zinc	28.57 a	4.07 a	25.10 a	4.56 a	3.31 a	2.59 a
Without zinc	27.25 b	4.11 a	26.54 a	4.57 a	3.28 a	2.64 a
H.S.D. (5%)	1.08	0.16	1.82	0.65	0.40	0.27
B rates (kg ha^{-1})						
0	27.48	4.15	26.07	4.68	3.33	2.51
1	29.12	4.10	25.15	4.86	3.55	2.55
2	26.25	4.15	25.08	5.35	3.63	2.73
3	28.24	4.13	27.58	4.30	3.11	2.61
4	28.47	3.93	25.22	3.63	2.85	2.67
Overall mean	27.91	4.09	25.82	4.60	3.30	2.61
C.V. (%)	5.03	5.00	9.18	18.48	15.94	13.54

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

It is noteworthy that, both in spring-summer and fall crops (Table 2 and 3), average leaf macronutrient concentrations were within the adequate ranges suggested by Cantarella et al. (1997), which should be 27.0-35.0, 2.0-4.0, 17.0-35.0, 2.5-8.0, 1.5-5.0, and 1.5-3.0 g kg^{-1} for N, P, K, Ca, Mg, and S, respectively.

Figure 2. Interaction between B rates and Zn application for Ca leaf concentration in fall crop (A); interaction between B rates and Zn application for Mg leaf concentration in fall crop (B); Cu leaf concentration in spring/summer crop as a function of B rates (C); Mn leaf concentration in spring/summer crop as a function of B rates (D); interaction between B rates and Zn application for B leaf concentration in spring/summer crop (E); interaction between B rates and Zn application for Zn leaf concentration in spring/summer crop (F). The letters correspond to a significant difference at 5% probability level ($p \leq 0.05$). ** and *: significant at $p<0.01$ and $p<0.05$, respectively. L.S.D. (low significant difference) = 1.45 (A), 0.90 (B), 0.98 (E) and 1.43 (F).



Leaf micronutrient concentrations and corn grain yield

Despite the known antagonism by competitive inhibition of Zn with Cu, Fe, and Mn, the addition of Zn had no influence on the leaf concentrations of these cationic micronutrients, neither in spring-summer nor fall corn plants (Tables 4 and 5). This result may be due to the low Zn rate applied in this study (2 kg ha^{-1}). Increasing B rates provided a linear increase in the leaf concentrations of Cu and Mn in spring-summer corn (Figures 2C, D). Conversely, studying the effect of increasing B and Zn rates in corn plant grown on Zn deficient soil, Adiloglu and Adiloglu (2006) verified that the concentrations of Cu, Zn, and Mn increased but those of Fe were adversely affected by Zn application, whereas B application affected them positively. By contrast, Fageria et al. (2002) reported that high B inputs resulted in low Zn, Fe, and Mn absorptions while increased Cu intake.

Table 4. Leaf concentrations of boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) and grain yield of spring/summer corn, affected by boron rates applied to the soil, with and without fertilization with zinc in the soil. Selvíria - MS, Brazil.

	B	Cu	Fe	Mn	Zn	Grain yield
	----------------------(mg kg^{-1})------------------------------					(kg ha^{-1})
With zinc	6.34	16.53 a	128.73 a	54.60 a	17.33	6547 a
Without zinc	4.32	15.47 a	139.20 a	51.87 a	16.40	6431 a
H.S.D. (5%)	0.44	1.99	12.98	4.64	0.64	464
B rates (kg ha^{-1})						
0	4.65	14.50(1)	125.50	50.50(2)	17.17	6095
1	4.77	15.00	132.17	51.33	16.17	6673
2	6.03	16.67	131.83	52.17	18.33	6631
3	5.61	14.33	138.67	58.00	16.50	7032
4	5.60	19.50	141.67	54.17	16.17	6316
Overall mean	5.33	16.00	133.97	53.23	16.87	6490
C.V. (%)	10.75	16.19	12.63	11.37	4.93	11.71

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

Table 5. Leaf concentrations of boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) and grain yield of fall corn, affected by residual of boron rates applied to the soil, with and without fertilization with zinc in the soil Selvíria - MS, Brazil.

	B	Cu	Fe	Mn	Zn	Grain yield
	----------------------------------(mg kg^{-1})----------------------------------					(kg ha^{-1})
With zinc	6.00	15.33	204.73 a	38.67 a	20.20 a	5279 a
Without zinc	6.20	15.53	208.33 a	39.87 a	19.93 a	5070 a
H.S.D. (5%)	1.97	3.18	18.21	3.98	1.13	523
B rates (kg ha^{-1})						
0	4.00	14.67	200.67	36.33	19.50(1)	5202
1	4.67	16.00	213.00	38.33	20.67	5788
2	6.00	12.33	221.50	42.17	21.83	5112
3	6.67	13.00	209.85	39.50	19.50	4816
4	9.17	21.17	188.83	40.00	18.33	4954
Overall mean	6.10	15.43	206.53	39.27	20.07	5174
C.V. (%)	25.59	26.86	11.50	13.21	7.31	15.59

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

Root elongation depends on the stability of cell walls (Shams et al., 2012). As B increases the stability of pectin fraction, this micronutrient may assist in root elongation, increasing the volume of soil explored. Hence, the absorption of some nutrients such as Cu and Mn, which are highly available in tropical acid soils, may increase, as well as their concentrations in foliar tissues. Such explanation may clarify the results observed in this study.

A significant interaction was found between Zn fertilization and B rates for the leaf B and Zn concentrations of spring-summer corn. Leaf B concentrations increased up to the rate applied of 2.75 kg B ha^{-1}, only when Zn was applied (Figures 2E, F). Leaf B concentration was higher when Zn fertilization was associated with B rates of 1, 2, 3, and 4 kg ha^{-1}, thus indicating a synergistic effect of the two elements. An adequate Zn concentration prevents plants from absorbing and accumulating excess B in leaves by increasing membrane integrity of root cells (TAVALLALI, 2017). Leaf Zn concentrations were also influenced by increasing B rates, only when Zn was applied, thus fitting a decreasing linear equation. Leaf Zn concentration was higher when Zn fertilization was associated with B rates of 1 and 2 kg ha^{-1} and without B application (0 kg ha^{-1}).

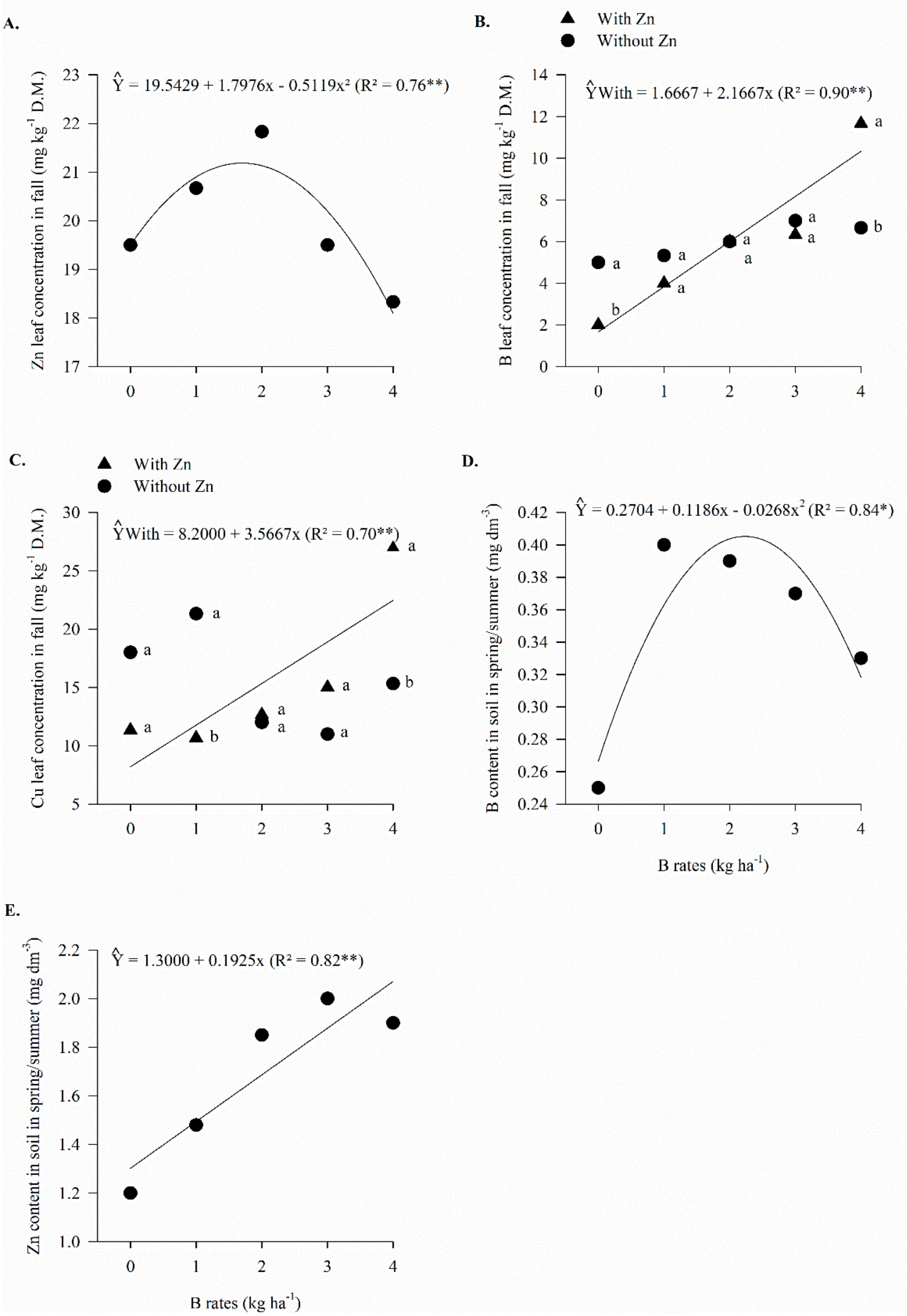
According to Tavallali (2017), the adverse effects of B deficiency and toxicity on pistachio (*Pistacia vera* L. cv. Badami) seedlings were alleviated by increasing Zn levels up to 10 mg kg^{-1} soil. Also, if B and Zn are adequate, synergism can be observed between both nutrients, as seen in the present research. Suitable amounts of B may speed up the effects of Zn by raising plant dry weight, photosynthesis, carbonic anhydrase activity, and chlorophyll contents (TAVALLALI, 2017).

Analyzing the statistical breakdown of Zn application into the B rates, except for control, leaf B concentrations were higher at all the B rates when Zn was applied (Figure 2E). This result points out a synergistic effect of Zn on B absorption by corn plants in clayey soil under B deficiency. Both B and Zn are essential to the optimal functioning of ATPase, the absence of one reduces the efficiency of the other (DAVARPANAH et al., 2016; SONGKHUM et al., 2018). In a study on corn grown in Oxisol, Jamami et al. (2006) evaluated plant response to different rates of B (0, 1, and 2 kg ha^{-1}) and Zn (0, 2, and 4 kg ha^{-1}) applied in planting furrow; these authors found neither increases in leaf concentrations of both nutrients nor interaction between their rates.

Boron doses showed residual effects only on Zn concentrations in fall corn leaves, with a quadratic fit and maximum values at 1.76 kg B ha^{-1} (Figure 3A). Again, synergism was evidenced by combination of these micronutrients. Likewise, Sinha et al. (2000) observed a synergistic interaction between Zn and B in black mustard (*Brassica nigra*) when both nutrients were either in low (positive effect) or excess (adverse effect) supply.

The interaction between Zn fertilization and B rates influenced significantly leaf B and Cu concentrations. When associated with Zn, leaf B and Cu concentrations increased linearly with increasing B fertilization levels (Figures 3B, C), among which the highest B level (4 kg ha^{-1}) provided the largest leaf B and Cu concentrations. Gupta (1993) reported that high B rates result in low Zn, Fe, and Mn absorptions and increased Cu absorption by plants. Gunesh et al. (2000) studied increasing rates of B and Zn on tomato crops and verified increased B concentrations in plants under no Zn-applied conditions. According to these researchers, B toxicity may be prevented by Zn application to plants. However, unlike most of the studies on B and Zn interaction in plant nutrition, the present study was carried out in an initially B-deficient soil with medium acidity and clayey texture, which can explain the difference between the results.

Figure 3. Zn leaf concentration in fall crop as a function of B rates (A); interaction between B rates and Zn application for B leaf concentration in fall crop (B); interaction between B rates and Zn application for Cu leaf concentration in fall crop (C); B content in soil in spring/summer crop as a function of B rates (D); Zn content in soil in spring/summer crop as a function of B rates (E). The letters correspond to a significant difference at 5% probability level ($p \leq 0.05$). ** and *: significant at p<0.01 and p<0.05, respectively. L.S.D. (low significant difference) = 2.68 (B), and 7.11 (C).



According to Cantarella et al. (1997), the adequate ranges of leaf B, Cu, Fe, Mn, and Zn concentrations for corn plants are 10-25, 6-20, 30-250, 20-200, and 15-100 mg kg^{-1}, respectively; therefore, the average leaf concentrations of Cu, Fe, Mn, and Zn found in both crops were adequate (Tables 4 and 5). Unlike these nutrients, leaf B concentrations remained below the acceptable range, even at higher B rates. However, neither deficiency nor toxicity symptoms were noted in plants, which can be explained by the low requirement of such corn hybrid for this element. Gupta (1993) stated that B concentrations in plant tissues may be related to several factors such as genetics, developmental stage, and environment (soil and climate).

Despite increases of 116 and 209 kg ha^{-1} in spring-summer and fall grains, respectively, Zn fertilization had no influence on these crops (Tables 4 and 5). This can be attributed to the average Zn content (1.2 mg dm^{-3}) available in the soil of the experimental area, which was enough for crop nutrition and development. For Fancelli and Dourado Neto (2000), the critical range is for this element is between 0.5 and 1.0 mg kg^{-1}. Besides that, the high clay content of the soil dramatically reduced Zn leaching from arable layer, enhancing its residual effect, which can explain the obtained results.

By contrast, Manzeke et al. (2014) found increases in corn yield after Zn application to the soil under deficiency conditions. Souza et al. (1998) found positive responses for corn grain yield to increasing Zn rates in planting furrows, but only until a rate of 5 kg ha^{-1}.

Increasing B rates did not significantly influence corn grain yield of both crops (Tables 4 and 5), despite the low soil B availability and the previously reported increased levels of B absorbed by corn when associated with Zn application. These results may be explained mainly by the low B requirement of the used corn hybrid, besides the high soil clay content, which could increase the adsorption of this element.

Trautmann et al. (2014) also did not find B influence on soybean grain yield, although other reports highlight the importance of B on reproductive development of crops (DEBNATH et al., 2011; MUHMOOD et al., 2014; BRUNES et al., 2015). Yet, Adiloglu and Adiloglu (2006) verified that shoot dry matter yield of corn plants grown in Zn-deficient soil decreased with B application, while increased with Zn application soil.

Soil contents of born and zinc

As for B and Zn in the soil after corn cultivation, contents were higher when Zn was applied, but only significant after spring-summer cultivation (Tables 6 and 7). These results explained the higher leaf B and Zn concentrations in spring-summer corn under Zn application (Table 4). Regarding the effect of B rates, a quadratic function was fitted, with concentrations of this nutrient in the soil increasing up to the rate of 2.21 kg B ha^{-1} after spring-summer cropping (Figure 3D). These results partially support the increased leaf B concentration up to the rate of 2.75 kg B ha^{-1} when Zn was applied to the soil (Table 4). Also, as a cation, Zn interacts with all plant nutrients in soil or absorbed by plants as anions, including NO_3^- (nitrate), PO_4^{3-} (phosphate), SO_4^{2-} (sulphate), Cl^- (chloride), BO_3^{3-} (borate), and MoO_4^{2-} (molybdate) (Prasad et al., 2016).

After spring-summer cropping, Zn soil content increased linearly as B rates were raised (Figure 3E), whereas leaf Zn concentrations was only influenced by B rates if Zn was applied to the soil, with reductions observed at B rates above 2 kg ha^{-1} (Table 6). Yet, B fertilization had no residual effect on soil B and Zn contents, although the same trend has been detected after the first corn crop (Table 7).

Table 6. Soil boron (B) and zinc (Zn) contents after cultivation of spring/summer corn, affected by boron rates applied to the soil, with and without fertilization with zinc in the soil. Selvíria - MS, Brazil.

	Soil B content	Soil Zn content
	----------------------------(mg dm^{-3})	----------------------------
With zinc	0.39 a	1.87 a
Without zinc	0.31 b	1.50 b
H.S.D. (5%)	0.07	0.25
B rates (kg ha^{-1})		
0	0.25(1)	1.20(2)
1	0.40	1.48
2	0.39	1.85
3	0.37	2.00
4	0.33	1.90
Overall mean	0.38	1.68
C.V. (%)	21.44	14.60

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

Table 7. Soil boron (B) and zinc (Zn) contents after cultivation of fall corn, affected by residual of boron rates applied to the soil, with and without fertilization with zinc in the soil. Selvíria - MS, Brazil.

	Soil B content	Soil Zn content
	---------------------------(mg dm^{-3})	---------------------------
With zinc	0.42 a	3.10 a
Without zinc	0.32 a	2.42 a
H.S.D. (5%)	0.13	1.09
B rates (kg ha^{-1})		
0	0.32	2.93
1	0.42	2.85
2	0.45	2.63
3	0.33	2.53
4	0.33	2.88
Overall mean	0.37	2.76
C.V. (%)	35.90	39.02

Means followed by identical letters in the column are not different from one another by Tukey test at the 5% probability level.

Soil B contents after spring-summer and fall corn crops (0.21 to 0.60 mg dm^{-3} B) are considered adequate according to Raij et al. (1997). Therefore, these findings may explain, in part, the lack of response in terms of grain yield to an increase in B rates.

Soil Zn contents increased considerably compared to those at the beginning of the experiment. These contents are deemed as high (>1.2 mg dm^{-3} Zn) according to Raij et al. (1997), being also higher if compared to those obtained by Ferreira et al. (2001), Jamami et al. (2006), and Prado et al. (2007), who found average and maximum values of 1.2 and 1.8 mg Zn dm^{-3} soil (Oxisol).

Average B and Zn increments in the soil after corn cropping may be due to the supply of these micronutrients (treatments) and soil organic-matter mineralization since the area was cultivated under no-tillage system and irrigated. Soil-applied B and Zn had a synergistic effect on corn nutritional status at rates of up to 2 kg B ha^{-1}, with higher soil contents resulting from the interaction of these micronutrients. Zinc fertilization and increasing B rates had no significant influence on grain yield for both spring-summer and fall corn crops, grown in a B-deficient and clayey soil in the Cerrado biome. Although both Zn and B promoted a slight increase in corn grain yield, and even under residual effect, we recommend an economic analysis before applying these micronutrients.

Conclusions

Zinc supplying increased leaf N contents in fall corn and S, B, and Zn contents in spring-summer corn. It also increased B and Zn levels in the soil after the first corn crop. Raising B rates led to a linear increase in leaf Cu and Mn contents of spring-summer corn and B contents up to the rate of 2.75 kg B ha^{-1}, only when Zn was applied. Yet, B rates higher than 2 kg ha^{-1} decreased leaf Zn content of both spring-summer and fall corn crops. When associated to Zn, B fertilization had a residual effect on fall corn, with a linear increase in leaf B and Cu concentrations, besides a positive effect on Ca and Mg when low B rates were used.

There is a synergistic effect between B and Zn applied to the soil on corn nutritional status up to B rates of 2 kg ha^{-1}, with higher soil contents resulting from the interaction thereof. Zinc fertilization and increasing B rates had no significant influence on grain yield both for spring-summer and fall corn plants, grown in a B-deficient and clayey soil in the Cerrado biome.

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