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Effects of Boron (B) doses and forms on boron use efficiency of wheat

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Abstract

Boron is one of the most limiting micronutrients in the grain production system in Brazil, mainly due to its complex dynamics in the soil-plant system. In this way, the objective of this study was to evaluate the efficiency of application forms and doses of boron with emphasis on wheat grain yield. The experiment was conducted in no-tillage system in an Oxisol with clay texture in Selvíria, MS. The experimental design was a randomized block design with four replicates arranged in a 4 x 3 factorial scheme, using four doses of boron (0, 1, 2 and 4 kg ha⁻¹) with boric acid source (B = 17%); and three application forms: (A1) in desiccation of the predecessor straw, along with herbicide; (A2) at the time of sowing, in soil along with the formulated fertilization seeding and (A3) foliar application along with the syrup of the herbicide (with the application of post emergent herbicide). The increase in boron doses reduced the recovery of apparent boron (RAB), boron uptake efficiency (BUPE) and agronomic efficiency (AE), but the application of 2 kg ha⁻¹ provided the highest boron utilization efficiency (BUtE) and wheat grain yield. We recommend application of 2 kg ha⁻¹ of wheat.

Keywords: Efficiency of borated fertilization, Borated fertilization, Boron time application, Boron uptake, *Triticum aestivum*. **Abbreviations:** RAB_Recovery of applied boron; PE_physiological efficiency; AGREC_agrophysiological efficiency; BUtE_boron utilization efficiency; BUpE_boron uptake efficiency; AE_agronomic efficiency; BHI_boron harvest index; a.i._active ingredient; O.M._organic matter

Introduction

Wheat (*Triticum aestivum* L.) is an annual cycle plant, considered among the cool season cereal, one that has greater economic importance with large grain yield capacity (Teixeira Filho et al., 2010; 2012; 2014; Marini et al., 2011; Theago et al., 2014). This cereal occupies over 17% of cultivable land in the world and represents approximately 30% of world grain production. In the periods from 2012 to 2016, the annual average area of wheat cultivation worldwide was approximately 220 million hectares, reaching 734 million tons in the 2015/2016 harvest (USDA, 2016).

Fertilization is recognized as one of the factors that favors the productivity and sustainability of the activity (Araújo, 2011; Galindo et al., 2016; 2017a; 2017b). Among the nutrients that most affect productivity, boron (B) is the most limiting micronutrient for crops, especially in the tropical soils, which are generally low in available B and organic matter, which is a major source of this nutrient to plants, affecting inadequacy in plant nutrition (Souza et al., 2011).

Boron is an essential element to plant growth, participating in several processes, such as sugar transport, lignification, cell wall structure, carbohydrate metabolism, RNA metabolism, respiration, indole acetic acid (IAA) metabolism, phenolic metabolism, ascorbate metabolism, besides it has function in cell wall synthesis and plasma membrane integrity (Calonego et al., 2010; Foloni et al., 2016). According to Metwally et al. (2017), B influences the germination of the pollen grain and pollen tube growth, increases flower glue and granulation, causes less male sterility and less grain puffiness. In addition to the better fertilization of flowers and grain formation, B interferes with the retention of newly formed spikes, besides acting on meristem growth, cell differentiation, maturation, cell division and plant growth (Tahir et al., 2009; Muhmood et al., 2014; Galindo et al., 2018).

As a result of its low mobility within the phloem, there is a need for a constant availability or supply of this nutrient during the vegetative phase of the plants (Calonego et al., 2010; Mantovani et al., 2013). Therefore, conduction of further studies on the ideal boron management and boron fertilization is of highly importance. However, there are few studies on B fertilization in wheat cultivation focusing on the best application method associated with the appropriate dose of this nutrient, aiming to improve the efficiency of boron fertilization.

The hypothesis of this study is based on the complex dynamics of boron in the soil-plant system, where it would

be possible to improve the use of boron fertilization as a function of the interaction between doses and forms of application with a positive effect on wheat grain yield. In view of the above, the objective of this study was to evaluate the efficiency of application forms and doses of B with emphasis on wheat grain yield improvement and proper management of borated fertilization.

Results

Effect of B doses in B efficiency and wheat grain yield

The increase of B doses negatively influenced BUPE and AE, adjusting to the decreasing linear equation (Table 1, Figure 3). However, it positively influenced BUtE and wheat grain yield up to the approximate dose of 2 kg ha⁻¹, with adjustment to the quadratic function (Table 1, Figure 3). The BUtE and grain yield were increase up to 36.6 and 13.8%, respectively, compared to mean of the other doses and the control dose (Table 1).

Effect of B application forms in B efficiency and wheat grain yield

B application forms influenced wheat grain yield, where application to the soil provided higher yield compared to the application in the predecessor straw and in the leaf tissue (Table 1). The increase in grain yield with B application in soil was 14.3 and 10.1%, respectively, compared to straw and foliar application, respectively (Table 1).

Effect of interaction between B doses and application forms in B efficiency and wheat grain yield

The interaction was significant for recovery of applied boron (RAB), where it is possible to observe that with the application of 1 kg ha⁻¹ of B in the straw, the recovery of applied boron was superior, compared to the application in soil and leaf tissue (Table 1, Figure 3). There was an adjustment to the linear decreasing function for straw and leaf applications (Table 1, Figure 3). PE, AGREC and BHI were not influenced by B doses and forms of application (Table 1).

Discussion

The requirement of wheat culture, the sensitivity of the root system in annual crops with respect to B was in the order of wheat > common beans > soybeans > rice > maize, meaning that the wheat crop requires more B for the development of the system root (Fageria, 2000). In this way, application of B in the soil may have provided greater amount of nutrient near the root, justifying the results obtained.

The lack of B is very common in tropical soils, which has caused great productivity losses in different crops (Mantovani et al., 2013). In addition, the amounts of B required for seed formation are generally greater than those required for vegetative growth (Marschner, 1995). For this reason, even in situations where the crop is cultivated in the soil with good B reserves, increases in grain yield can be obtained with boron fertilization. Besides, the B content in the soil is below the adequate range according to Raij et al.

(1997) (0.17 mg dm⁻³ B in soil), while the content stipulated as the average is above 0.20 mg dm⁻³. The Brazilian Cerrado soil have low O.M. content, which is the main source of B for the crops (21 g dm⁻³ in the present study) and the high requirement of this nutrient for the wheat crop, demonstrating that the management of boron fertilization can be beneficial and positive in grain yield, as verified in this study.

Boron is an essential element to plant growth. It participates in several processes, such as sugar transport, lignification, cell wall structure, carbohydrate metabolism, RNA metabolism, respiration, indole acetic acid (IAA) metabolism, phenolic metabolism, ascorbate metabolism. Furthermore, B has function in cell wall synthesis and plasma membrane integrity (Calonego et al., 2010), influencing the germination of the pollen grain and pollen tube growth, increasing flower glue and granulation, causing less male sterility and less grain puffiness (Metwally et al., 2017). In addition to the better fertilization of flowers and grain formation, B interferes with the retention of spikes, beside acting on meristem growth, cell differentiation, maturation, cell division and plant growth (Tahir et al., 2009; Muhmood et al., 2014). These innumerable functions of the B probably increases the number of spikelets per spike, together with the greater utilization of this nutrient, increasing BUtE, influencing in a positive way the grain yield.

It is noteworthy that, the dose that produced higher grain yield (2 kg ha⁻¹ of B) resulted in higher PE compared to the doses of 1 and 4 kg ha⁻¹ which only produced 29.4 and 73.7% higher, respectively, and also provided an increase of 36.4% in BHI, compared to the control (Table 1). The dose of 2 kg ha⁻¹ also increased the shoot dry matter yield, compared to the amount of accumulated boron in shoot and the amount of accumulated boron in shoot and the amount of accumulated boron. According to Galindo et al. (2018), boron management in wheat crops in Brazilian conditions is very important to provide economical return, ensuring profitability from production of irrigated wheat.

Similar results were reported by Souza et al. (2011), working with 0; 0.6; 1.2; 1.8 and 2.4 kg ha⁻¹ of B in common bean. They obtained maximum grain yield at the dose of 1.8 kg ha⁻¹ of B. Muhmood et al. (2014), applied boron fertilization on wheat and reported higher grain yield at the dose of 2 kg ha⁻¹. Debnath et al. (2011) found a higher yield of wheat grain at a dose of 1.9 kg ha⁻¹ B. However, Brunes et al. (2015) verified that boron fertilization, applied at sowing or tillering in doses between 2.5 and 3.0 kg ha⁻¹ caused an increase in

the number of seeds and spikes per plant, but with a reduction of seed yield per plant, mass of 1000 seeds and the hectoliter mass, unlike the one verified in the present work. However, a drastic reduction of grain yield was observed above the dose of 2.8 kg ha⁻¹ of B.

The application of boron highly influenced the wheat crop, providing greater grain yield, which can be explained by the numerical increase of PE and AE. The PE was increased 60.93 and 14.15% and AE in 34.2 and 17.1%, when compared to the application on straw and foliar tissue, respectively. In addition it provided higher BUtE and BUPE of 12.5 and 21.7%, respectively, compared to straw application.

Doses (D) (kg ha ⁻¹)	RAB	PE	AGREC	BUtE
(%	kg D.M./ g of B accumulated	kg grains/ g B accumulated	g of B accumulated/ g of B applied
0	-	-	-	-
1	1.04	131.17	6.78	0.71
2	0.67	185.72	8.88	0.96
4	0.40	48.88	12.47	0.18
Forms (F) ¹				
Straw	0.97	63.53 a	17.45 a	0.56 a
Soil	0.57	162.62 a	4.89 a	0.64 a
Foliar	0.56	139.61 a	5.79 a	0.64 a
L.S.D. (5%)	0.42	176.22	15.35	0.51
Overall Mean	0.70	121.92	9.38	0.62
C.V.	10.96#	25.33##	27.57##	13.42#
F test				
D	20.574**	2.414ns	0.037ns	13.006**
F	11.511**	1.713ns	2.135ns	0.795ns
D x F	4.006*	1.242ns	1.315ns	1.286ns
Doses (kg ha ⁻¹)	BUpE	AE	BHI	Grain Yield
	g of B accumulated/ g of	kg grains/ g B apllied	B accumulated in grains/	Kg/ ha
	B available		B accumulated in grains +	
			straw	
0	-	-	0.07	3638.93
1	0.035	0.55	0.14	4094.27
2	0.020	0.37	0.11	4223.36
4	0.010	0.11	0.12	3883.16
Forms				
Straw	0.018 a	0.27 a	0.13 a	3695.06 b
Soil	0.023 a	0.41 a	0.10 a	4310.86 a
Leaf	0.023 a	0.34 a	0.10 a	3873.88 b
L.S.D. (5%)	0.007	0.33	0.05	427.00
Overall Mean	0.022	0.34	0.11	3959.93
C.V.	19.61	11.84#	2.77#	10.51
F test				
D	95.736**	14.020**	2.116ns	9.390**
F	2.269ns	1.963ns	1.205ns	6.952**
	1 205	2 212 mg	1.074mg	1 021 ^{ns}

Table 1. Recovery of applied boron (RAB), physiological efficiency (PE), agrophysiological efficiency (AGREC), boron utilization efficiency (BUtE), boron uptake efficiency (BUpE), agronomic efficiency (AE), boron harvest index (BHI) and wheat grain yield as a function of B doses and forms of application.

Means followed by the same letter in the column of not differ by the Tukey test at 0,01; **, *, ^{ns} Significant at p < 0.01, 0.01 , and not significant, respectively.¹Straw, soil and foliar represents, respectively the treatments A1) in desiccation of the predecessor straw, together with herbicide (2 weeks before wheat sowing); A2) at the time of sowing,in soil along with the formulated fertilization seeding and A3) foliar application with the application of post emergent herbicide (20 days after emergence).# Corrected data following equation (x + 0.5) ^{0.5}

Corrected data following equation $(x + 0.5)^{0.5}$ ## Corrected data following equation $[(x + 0.5)^{0.5}]^{0.5}$



Fig 1. Study area at the Selvíria, Mato Grosso do Sul, Brazil (20°22'S, 51°22'W, altitude of 335 m).



Rainfall - Av. T. - Max. T. - Min. T. - Air Rel. Humi.

Fig 2. Rainfall, air relative humidity, and maximum, average, and minimum temperatures obtained from the weather station located on the Education and Research Farm of FE / UNESP during wheat cultivation in the period of May to October 2016.



Fig 3. Interaction between boron doses and forms of application in recovery of applied boron (RAB) (A). The letters correspond to a significant difference at 5% probability level ($p \le 0.05$). ** and *: significant at p<0.01 and 0.01<p<0.05, respectively and L.S.D. = 0.73; boron utilization efficiency (BUtE) (B); boron uptake efficiency (BUpE) (C); agronomic efficiency (AE) (D); and wheat grain yield (E) as a function of B doses. Error bars indicate the standard error of the mean (n = 4).

It is important to point out that the results observed for RAB, PE, AGREC, BUtE, BUpE, AE and BHI were relatively low. The

efficiency of boron fertilization as a function of doses and forms of application was low when compared to other

nutrients, i.e. nitrogen, which varies around 40 to 50% (Galindo et al., 2017c). It is mainly due to the complex dynamics of this nutrient with low mobility within the phloem (Calonego et al., 2010; Mantovani et al., 2013), but with high mobility in soil, especially when applied in the form of boric acid, with high solubility in water and low reactivity with the soil, making it susceptible to leaching (Trautmann et al., 2014).

Ali et al. (2015), applied six levels of boron (0, 0.5, 1, 2, 3 and 5 kg ha⁻¹), on tobacco in the form of boric acid in the soil and reported fertilizer use efficiency of 2.8%, 75% higher than the present study. However, Shah et al. (2014), studying boron use efficiency in twenty cotton genotypes found average BUtE with boron fertilization in the dose of 2 kg ha⁻¹ of 0.099 g of B accumulated/g of B applied, 89.6% lower than that observed in the present study.

With respect to the reduction in BUpE and AE with increasing B doses, this result can be attributed to the loss of B, as clearly described in the literature. Boron may encounter greater losses and less utilization by the crops when applied excessive, since plant nutritional demand is limited. Plants are able to absorb a certain quantity of nutrients in a certain time. The excess of applied B may not be absorbed by plant and can be lost, decreasing the efficiency of fertilization with higher B rates, as stated in the literature as the law of diminishing returns (Galindo et al., 2016).

Based on the obtained results, it is recommended to fertilize the irrigated wheat at the dose of 2 kg ha⁻¹ of B, favoring high grain yield and optimizing the productive system of this crop, which can be grown on a larger scale in the low altitude Cerrado region.

Materials and methods

Field sites and material description

The research was conducted at the experimental station located in Selvíria, Mato Grosso do Sul ($20^{\circ} 22'$ S, $51^{\circ} 22'$ W, altitude of 335 m), Brazil, in 2016 (Figure 1). The average temperature was 23.5 °C, the annual average precipitation was 1,370 mm, and the annual average relative air humidity was 70-80% (Figure 2). The soil in the experimental area was classified as Oxisol (Latossolo Vermelho distrófico) with clayey texture (Embrapa, 2013).

The chemical attributes of the soil (depth of 0-0.20 and 0.20-0.40 m) were determined in 2016 before the initiation of the experiment, following the methodology proposed by Raij et al. (2001). The following results were obtained: 0-0.20 m layer: 19 mg dm⁻³ P (resin); 10 mg dm⁻³ of S-SO₄; 21 g dm⁻³ organic matter; 5.0 pH (CaCl₂); K, Ca, Mg, H + Al and Al = 2.1; 19.0; 13.0; 28.0 and 1.0 mmol_c dm⁻³, respectively; Cu, Fe, Mn, Zn (DTPA) = 3.1; 20.0; 27.2 and 0.8 mg dm⁻³, respectively; 0.17 mg dm⁻³ B (hot water) and 55% base saturation; and in the 0.20-0.40 m layer: 17 mg dm⁻³ P (resin); 30 mg dm⁻³ of S-SO₄; 16 g dm⁻³ organic matter; 4.8 pH (CaCl₂); K, Ca, Mg, H + Al and Al = 1.2; 11.0; 8.0; 28.0 and 2.0 mmol_c dm⁻³, respectively; Cu, Fe, Mn, Zn (DTPA) = 2.1; 10.0; 10.7 and 0.2 mg dm⁻³, respectively; 0.11 mg dm⁻³ B (hot water) and 42% base saturation.

The granulometric analysis (depth of 0–0.20 and 0.20-0.40 m) presented the following results: 433, 471 and 90 g kg⁻¹ of clay, sand and silt, respectively, in 0-0.20 m layer and 447,

471 and 82 g kg⁻¹ of clay, sand and silt, respectively in 0.20-0.40 m layer.

The experimental area has been cultivated with annual crops for more than 27 years, and the no-tillage system has been used for the past 10 years, with corn as predecessor crop. The corn straw was collected to estimate the accumulation of nutrients: 62.3; 11.5; 45; 44.5; 17.8 and 15.8 kg ha⁻¹ of N, P, K, Ca, Mg and S, respectively, and 217.9; 178.1; 1940.9; 1210.8 and 267.1 g ha⁻¹ of B, Cu, Fe, Mn and Zn, respectively.

Experimental design

The statistical design was randomized blocks with four replications in a 4×3 factorial design: four boron doses (0, 1, 2 and 4 kg ha⁻¹) with boric acid source (B = 17%); and three apllication forms: (A1) in desiccation of the predecessor straw, together with herbicide (2 weeks before wheat sowing); (A2) at the time of sowing, in the soil along with the formulated fertilization seeding and (A3) foliar application with the application of post emergent herbicide (20 days after emergence). The experimental plots were composed of twelve 5 m lines spaced at a distance of 0.17 m, and the useful area of the plot considered was the central eight lines, with the exclusion of 0.5 m from the ends.

Crop development

The herbicides used in the experimental areas were glyphosate (1800 g ha⁻¹ of a.i.) and 2,4 - D (670 g ha⁻¹ of a.i.) for desiccation. The products were applied two weeks before wheat cultivation. On the basis of the results of soil analysis and the need to increase base saturation to 70%, as recommended by Cantarella et al. (1997), 1.2 t ha⁻¹ of dolomitic limestone (PRNT = 80% CaO = 28% and MgO = 20%) were applied to the soil, 60 days before sowing wheat in 2016. Furthermore, on the basis of the results of soil analysis and culture requirements, 275 kg ha⁻¹ of the formula 08-28-16 were supplied for sowing fertilization. For seed treatment, the fungicides carbendazim + thiram (45 g + 105 g of a.i. per 100 kg of seed) and the insecticides imidacloprid + thiodicarb (45 g + 135 g of a.i. per 100 kg of seed) were used.

The wheat crop was irrigated using a center pivot sprinkling system, with a mean water depth of 14 mm and an irrigation interval of approximately 72 h. The cultivar used was CD 1104 with mechanical seeding on May 03, 2016 with a density of 70 seeds per meter. The seedlings emerged 5 days after sowing on May 08, 2016.

The weeds were managed with the application of the herbicide metsulfuron-methyl (3 g ha⁻¹ of a.i.), 20 days after emergence (DAE) of wheat. Nitrogen fertilization was performed manually on June 08, 2016 with 30 DAE, with urea as source (45% N). The fertilizer was spread on the soil surface without incorporation on the sides and at approximately 8 cm from the sowing lines to avoid contact of the plants with the fertilizer at the dose of 140 kg ha⁻¹ of N. After cover fertilization, the area was irrigated by sprinkling (depth of 14 mm) at night to minimize losses by volatilization of ammonia, which is common in irrigated wheat. The plants in useful area of the plot were harvested manually at 120 DAE on September 8, 2016.

Analytical procedures

At harvest time, total dry matter accumulation and grain yield were determined, which was used to calculate B fertilization efficiencies in addition to the B content in shoot and grain. This was determined by proposed methodology of Malavolta et al. (1997).

The efficiency calculations of boron fertilization were defined using the adapted formulas according to Fageria et al. (2010):

A) Recovery of applied boron (RAB) = B accumulated (g) with fertilization – B accumulated (g) without fertilization / B dose applied (g) x 100; in %);

B) Physiological efficiency (PE) = (Biological productivity (straw and grains) with B fertilizer - biological productivity without B fertilizer)/ (Accumulation of B in shoot and grains with fertilizer - accumulation of B in shoot and grains without fertilizer);

C) Agrophysiological efficiency (AGREC) = (Grain yield with B fertilizer - grain yield without B fertilizer)/ (Accumulation of B in shoot and grains with fertilizer - accumulation of B in shoot and grains without fertilizer);

D) Boron utilization efficiency (BUtE) = is the product of physiological and apparent recovery efficiency. It can be calculated by: PE × RAN;

E) Boron uptake efficiency (BUpE) = Accumulation of B in shoot and grains / total amount of B disponible (B fertilizer + soil) (adapted of Masclaux-Daubresse et al., 2010);

F) Agronomic efficiency (AE) = (grain yield with fertilizer - grain yield without fertilizer) / (amount of B applied);

G) Boron harvest index (BHI) = Accumulation of B in grains / accumulation of B in grains + straw (adapted of Barraclough et al., 2010).

The yield was determined by counting the spikes of plants present in the four useful lines of each plot. After mechanical tracking, the grains were quantified and the data were converted into kg ha⁻¹ at 13% (wet basis).

Statistical analysis

The results were subjected to analysis of variance (F test) and Tukey's test at 5% of significance for the comparison of the average yields obtained with different B application forms. The regression equations were adjusted to the effect of B doses using the Sisvar software (Ferreira, 2011).

Conclusion

The increase in boron doses positively influences BUtE with positive reflex in wheat grain yield until 2 kg ha⁻¹, but reduce BUpE and AE. The application of B in the soil provided higher grain yield. The application of B to the soil at the time of sowing in the approximate dose of 2 kg ha⁻¹ provided the highest wheat grain yield.

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